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Seismicity Rates for Eastbay Faults

J. F. Scheimer

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March 29, 1984

Lawrence Livermore National Laboratory

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J.F.Scheimer and J.M.Mills

Abstract

Using both maximum-likelihood and least-square techniques, we have calculated both a- and b-values for nine source zones in the Eastbay region. The source zones include the Hayward, Calaveras, Greenville, Las Positas, and Verona Fault zones, as well as diffuse source zones in the Diablo Range. We have made use of a number of earthquake catalogs, including those of the U.S. Geological Survey (USGS), the California Division of Mines and Geology (CDMG), and the Seismographic Station at the University of California, Berkeley (UCB). Taken together, these catalogs provide information for the time period 1900 to the present, although they vary in completeness and time coverage. The b-values calculated for the Hayward and Calaveras Faults using the USGS catalog (which begins in 1969) are 0.90 and 0.95 which are consistent with those derived by other researchers. The b-values calculated for the same zones using the CDMG catalog, which includes data recorded since the beginning of the century, are 0.95 and 0.78 respectively. We have used a number of permutations of technique and catalog to calculate a- and b-values for all of the zones. In addition the variance of the b-values calculated using the maximum-likelihood estimator have been calculated; and the statistical significances of variations in b-values between different populations have been estimated.

Introduction

An accurate, up to date evaluation of possible geologic hazards at the LLNL site has been the goal of the Site Seismic Hazard Program. A major part of this evaluation has been the determination of the degree of hazard at the site due to strong ground shaking resulting from moderate to large earthquakes in the San Francisco Bay Area. Current state of the art in seismic hazard determination utilizes a probabilistic approach. In a probabilistic hazard determination, an attempt is made to derive both the best possible representation of the local seismo-tectonic setting and a quanitative estimate of the errors in estimating the parameters that describe the setting. A significant parameter which is input to such calculations is the estimate of recurrence rate of seismic events of various sizes for given source regions. These recurrence rates may be determined from direct examination of the geologic record, which gives the long-term geologic slip rate for a given fault, or by examining the statistics of recorded seismicity for these regions. In practice, both of these approaches are used since both have shortcomings.

The use of geologically determined slip rates gives a long-term estimate of of the total deformation, but any variation in strain rate is usually unresolvable and errors in the estimates are difficult to evaluate. In addition, there is no standard procedure for discriminating between the slip that occurs during earthquakes and aseismic slip or creep. On the other hand, we can accurately quanitfy the errors on our estimates of seismically determined recurrence rates, but we are severely restricted in the time period for which seismicity has been accurately monitored. This rather short time window (as compared to geologic time scales), coupled with the variability of magnitude estimates, can tend to reduce the value of such estimates. As part of the LLNL Site Seismic Safety Program's hazard evaluation, both geologic slip rates and seismicity rates have been used in the determination of recurrence rates. This report describes the basic data and analyses used to evaluate seismicity rates from instrumentally recorded earthquakes in the east San Francisco Bay Area. These data are the basis for later reports which discuss the actual seismic hazard determinations.

In our determination of seismicity rates, we have made use of all pertinent seismicity catalogs. This has required the acquisition of data from a number of sources, followed by careful examination of the completeness of each seismicity catalog. The seismic source zones to be used in the later hazard analyses were then outlined, based both on geologic and seismological evidence. In this report we will describe, in detail, the derivation of seismicity rates for each of these zones from seismicity catalogs using methods based on the empirical relation between earthquake magnitude and recurrence derived by Gutenberg and Richter (1954). This relationship is given by

$$\log n(M) = a - bM, \qquad (1)$$

When this equation is applied to a set of earthquakes in a magnitude range from M to $M+dM$ then; $n(M)dM$ is the number of earthquakes in that magnitude range, the constant a is related to the rate of earthquake occurrence, and the constant b is related to the relative distribution of small versus large earthquakes. Given a catalog of n earthquakes, the constant b (known as the b-value) can be estimated by a number of methods. Gutenberg and Richter (1954) used the least-squares technique to fit a straight line in magnitude-log number space to the function $\log n(M)$. Utsu (1965) proposed a new method of estimating

b, which was shown by Aki (1965) to be the maximum-likelihood estimate. Aki (1965) also showed how to calculate confidence limits on the estimate for a given sample. Utsu (1966) then derived an exact form for the probability density function for the value of b and derived a method to test the statistical significance of the difference between two different populations of earthquakes.

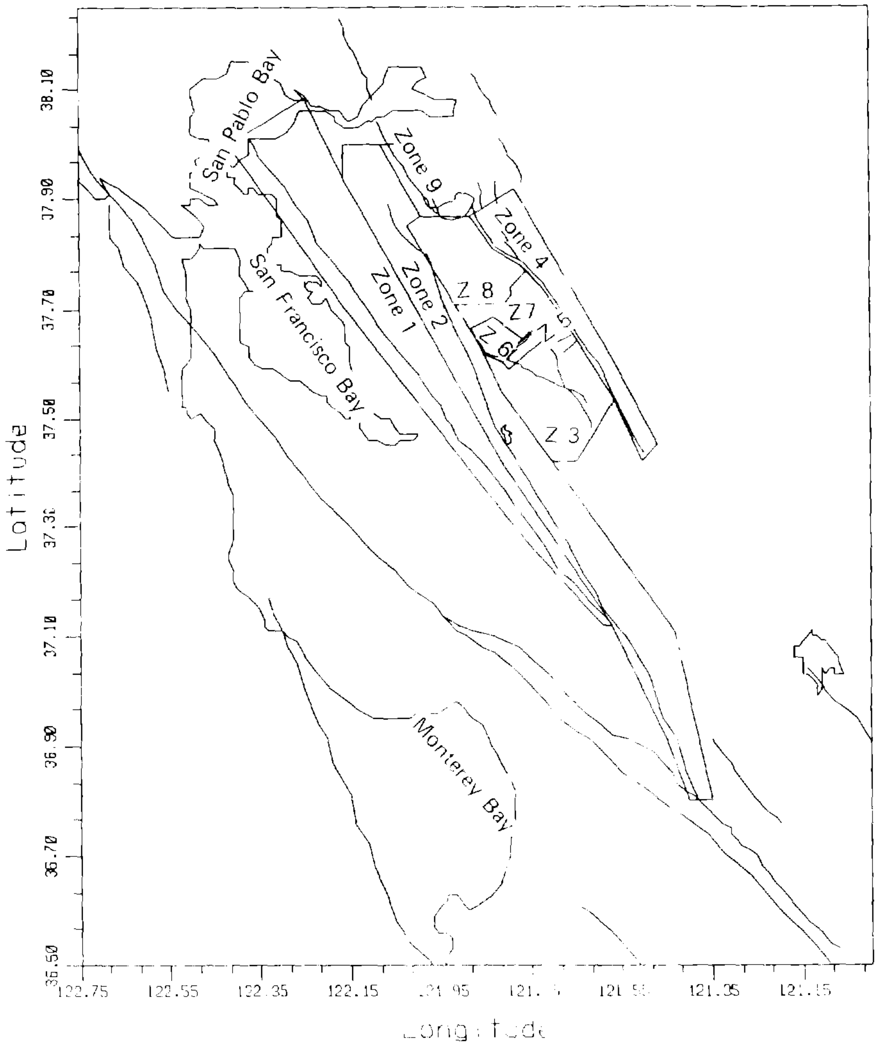

Figure 1. Regional map showing the outlines of the source zones chosen for this study. Seismicity to the east of the Greenville Fault and to the north and south of the San Francisco Bay region was not considered.

We have used a combination of the least-squares and maximum-likelihood methods to estimate a- and b-values for nine regions in the east San Francisco Bay Area. to aid in the estimation of the earthquake hazard at the Lawrence Livermore National Laboratory (LLNL) site. The choice of source zones (Figure 1) was based on a number of criteria, including alignment of seismicity, tectonic history, and surface geologic mapping. The important consideration in this zonation was to find any characteristics which might show that one set of earthquakes was physically distinct in some way from the other sets. The final zonation was based on input from geologists, geophysicists, and seismologists in the

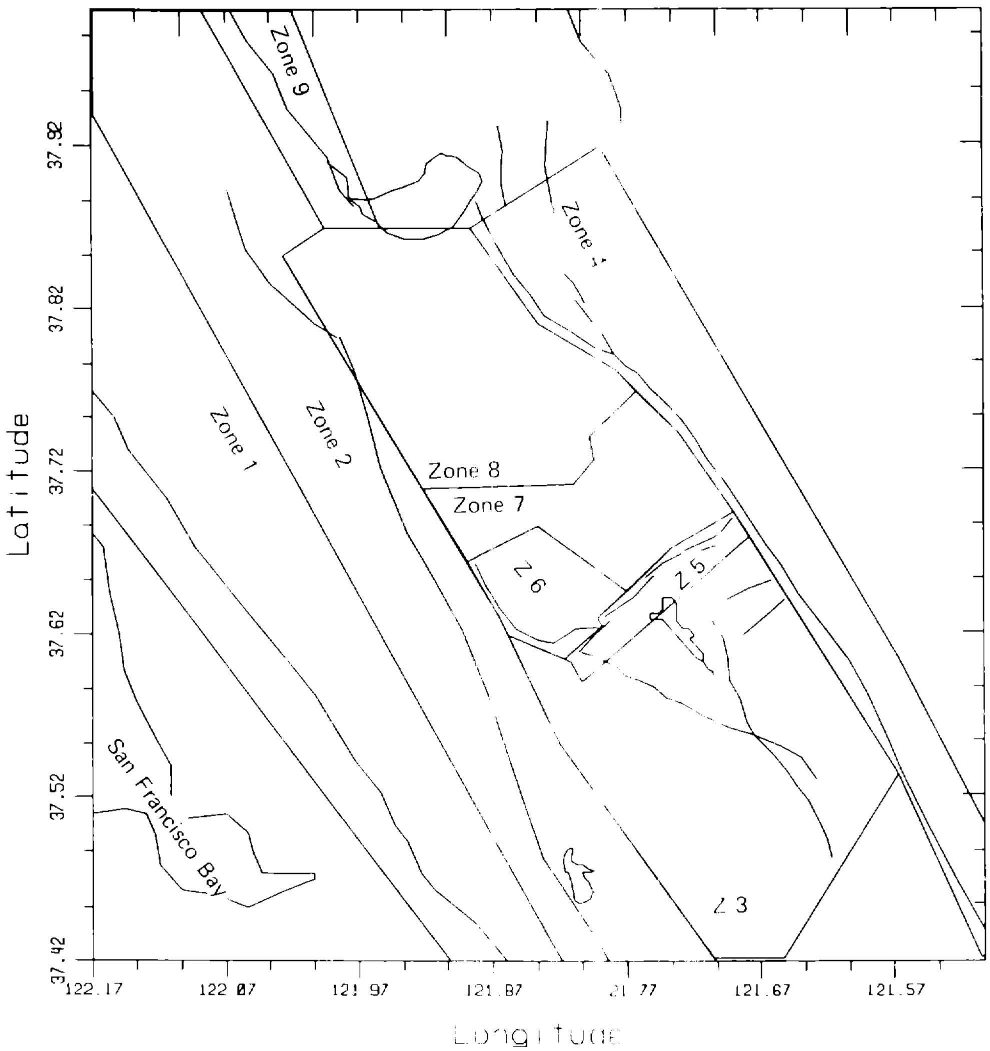

Figure 2. Detail of the source zones in the Diablo Range. Zones 3,7, and 8 correspond to diffuse source zones, while the remaining zones define specific fault zones.

LLNL Site Seismic Survey Program. Overall, our zones are quite similar to those chosen by Pfluke and Steppe (1973). However, recent detailed tectonic studies of the Livermore Valley region lead us to subdivide certain zones(Carpenter *et al.*, 1982). In particular, we have subdivided one zone of Pfluke and Steppe's that included Mt. Diablo, the north Calaveras Fault, and other faults, into seven zones. An enlarged view of the zones within the Livermore region is shown in Figure 2.

The zones shown in Figure 2 were selected, in part, because they separate LLNL-located seismicity associated with different mapped faults into distinct groups. These zones include the Hayward Fault region, Calaveras Fault region, the Diablo Range region, Greenville Fault region, Las Positas Fault region, Verona Fault region, Livermore Valley region, Danville region, and the Concord Fault region (zones 1-9, respectively). A careful relocation of seismicity in the region using appropriate velocity models for different source areas (Taylor and Scheimer, 1982) results in virtually all seismic events for a given zone

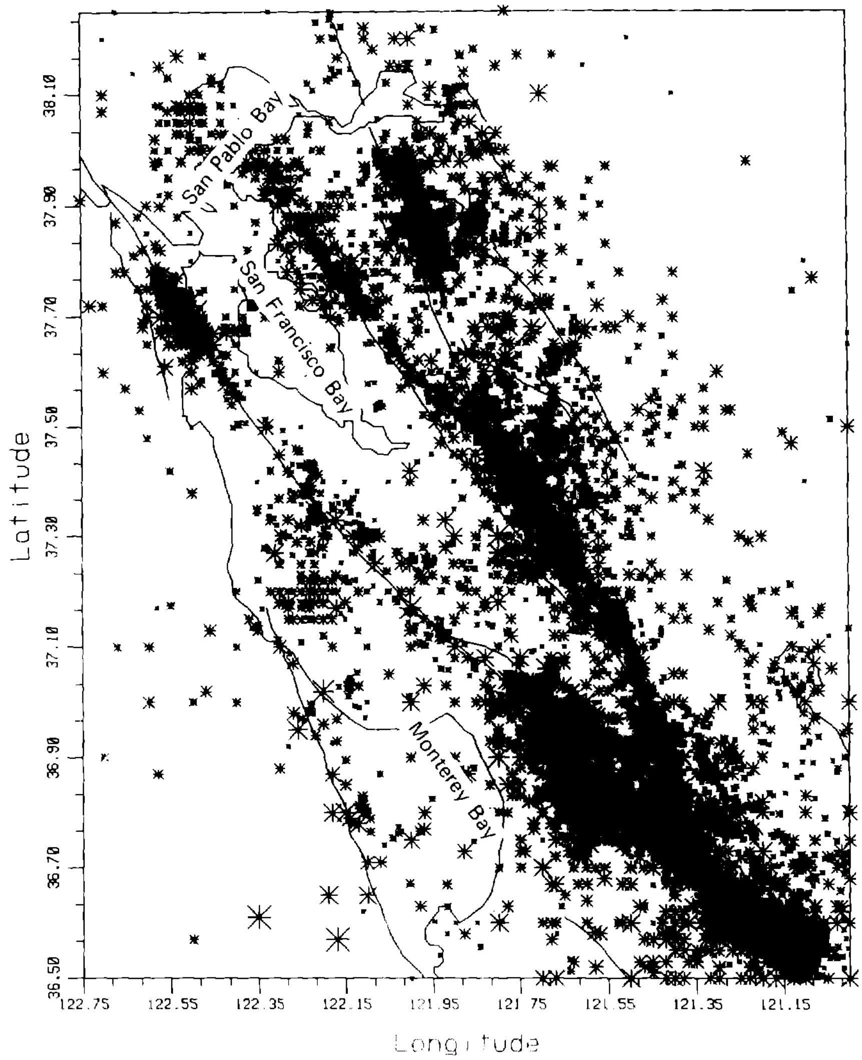

Figure 3. Earthquake epicenters for the Livermore Region based on the CDMG catalog. This catalog covers the time period 1900-1974, and is based on data from the UCB and USGS catalogs and historical records.

being plotted within the boundaries of that zone. This means that there is a minimum of inclusion of earthquakes into one zone that should have been associated with another.

Data Sets

Any effort to accurately determine seismicity rates for a given area is highly dependent on the quality of the available seismicity catalogs. In order to estimate *a*- and *b*- values for a given fault we must define a region that contains all reported earthquakes generated by that particular fault and for us to establish the limiting magnitude above which we believe that catalog is complete (i.e. the magnitude above which no earthquakes are believed to have been excluded). The regions shown in Figure 2 are appropriate for this purpose. To estimate the completeness and stationarity of each catalog used in this study, we have plotted reported magnitudes of all earthquakes in each catalog as a function of time.

Four data sources were used in our calculations. The first data set (Figure 3), a statewide catalog of California seismicity for 1900-1974 compiled by Real,*et al.* (1977),

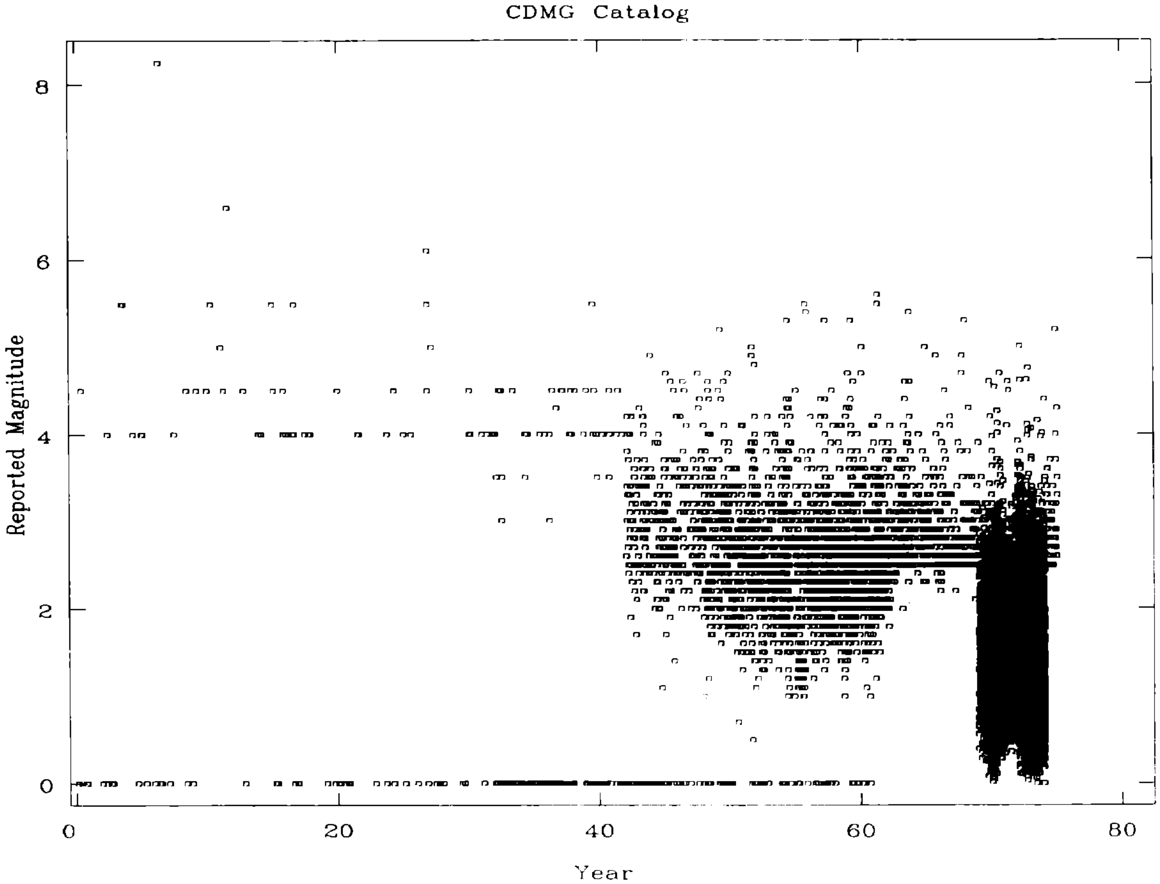

Figure 4. Magnitudes of events from the CDMG catalog shown in Figure 3. are plotted as a function of time to examine the completeness of the catalog. For years between 1943 and 1977, this plot shows the catalog to be complete to about M_L 2.5.

utilizing USGS, CalTech, UCB, and other catalogs, was published by the California Division of Mines and Geology. Because these data consist only of summary information about each event, such as locations and magnitudes, and not actual phase data, we are unable to improve the quality of the locations. Earthquakes that were reported but for which no magnitude estimate was given have been plotted as $M_L = 0$. Variations in the minimum reported magnitude are obvious. The catalog appears to be deficient even for magnitudes between 4.0 and 6.5. for years before 1943. For years between 1950 and 1977, this catalog appears to be complete down to M_L 2.5 (Figure 4.).

A major component of the CDMG data set is the University of California, Berkeley, Seismographic Station catalog of earthquakes (Figure 5.). The UCB data set covers the time period from 1910 through mid-1980 and is complete between 1943 and 1980 to about M_L 2.5 (Figure 6.). From 1910 through the mid-1920s, most of the seismometers in use were Weichert instruments (Bolt and Miller, 1975). These instruments were replaced with Wood-Anderson seismometers between 1926 and 1930. The UCB catalog includes only 17 reported magnitudes prior to 1931, only two of which were located within the area of interest shown in Figure 5. During the tenure of Perry Byerley (apparently starting in about 1941) the Seismographic Station routinely reported magnitudes to less than 2.0.

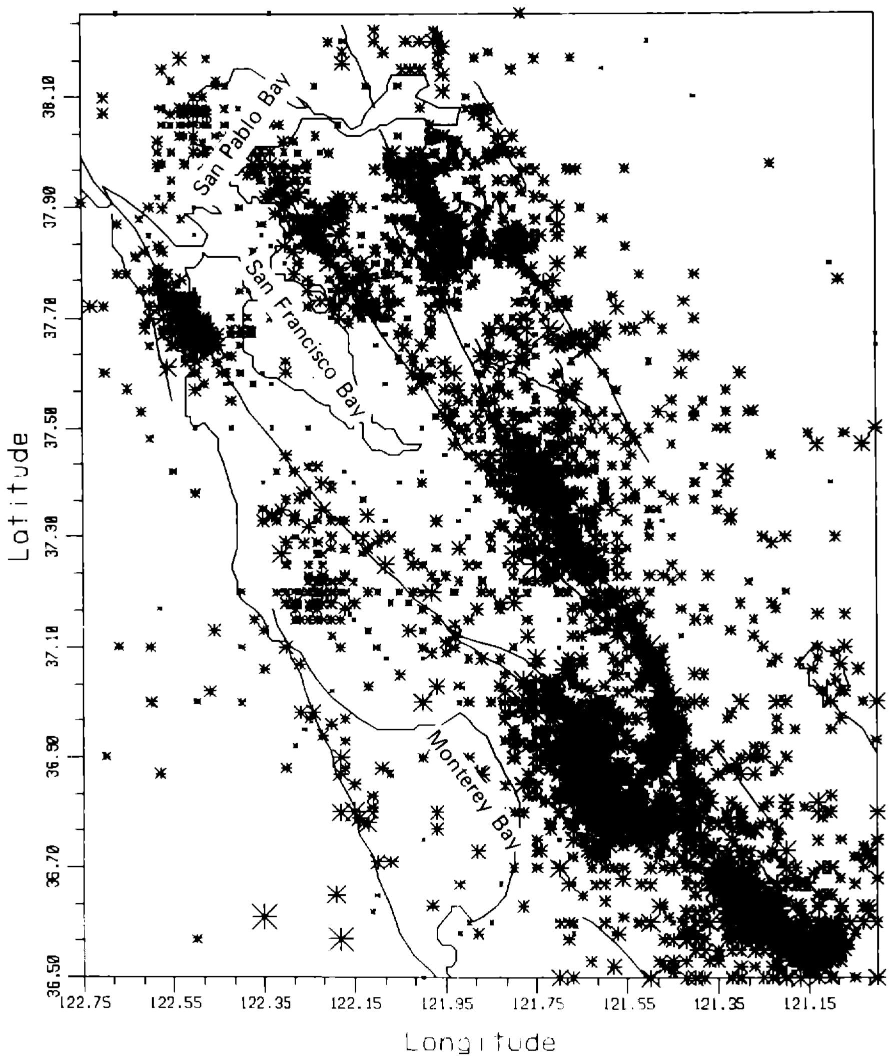

Figure 5. Earthquake epicenters as recorded in the UC Berkeley Seismographic Station catalog for the time period 1910 through mid-1982.

This can be seen in the plots for both the CDMG and the UCB catalogs. Later, about 1960, a decision was made (Tom McEvilly, personal communication) to report no magnitudes below 2.5. This is also clearly seen in the plots of magnitude vs time. However, we cannot guarantee the catalog's completeness before about 1950. After about 1963, few events smaller than M_L 2.5 were routinely located. Even so, this data set represents the only uniform treatment of magnitude estimation available for the Bay Area.

Most epicentral locations (at least in the CDMG and UCB catalogs) appear to be reported to no better precision than about 1.0 minute (in latitude and longitude) prior to 1962 and about 0.1 minute after 1962. After the installation of the USGS CALNET (in 1969), the location precision and accuracy improved dramatically (see Figure 7.). Therefore, we also obtained from the USGS the CALNET summary earthquake data for the period 1969 through mid-1982. This third data set is complete to smaller magnitudes than either the CDMG or UCB catalogs, but the magnitude estimates were made using a variety of methods. (See Figure 8.) For the period from January 1969 through May 1970,

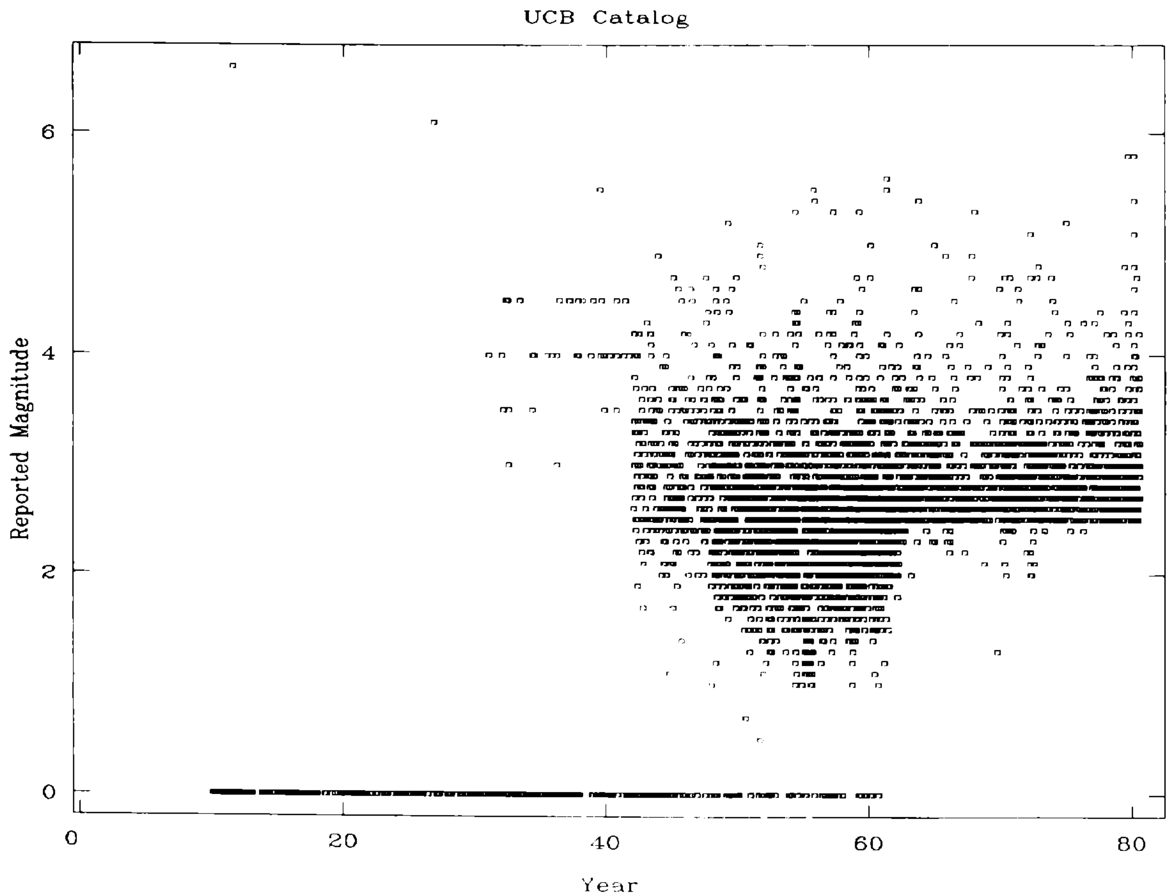

Figure 6. Magnitudes of events from the UCB catalog as plotted in Figure 5. are plotted against time to illustrate the completeness of this dataset. The catalog appears to be complete down to M_L 2.5 after about 1950.

the magnitudes were estimated using a peak velocity measure proposed by Eaton (1969). After this time, magnitudes less than 3.0 were estimated using the coda duration method described by Lee *et al.* (1972a). Magnitudes greater than 3.0 were, in general, changed to M_L values calculated by UCB. This catalog is complete down to magnitude 1.0 for those regions where the station coverage is extensive but, during the time period we were using, a number of stations were added to the east and to the south. For these regions, the completeness of the catalog is difficult to estimate for intermediate years (1975-1981) when the minimum magnitudes reported appear to increase to near M_L 1.0.

A modified version of the USGS data set was used as our fourth data set, which we refer to as the LLNL data set. Since the locations provided to us by the USGS had been calculated using an average central California model, we also obtained the P- and S-wave arrival time data for those earthquakes which had occurred in a region bounded by 37°42′ N and 38°00′ N latitude, and by 121°28′ W and 120°10′ W longitude. This region was further subdivided into three smaller regions as shown in Figure 9.

Velocity models and station corrections were derived for each of these regions, using both earthquakes and calibration shots, following the methodology outlined in Taylor and Scheimer (1981). Table 1a shows the velocities and station delays used for each of the regions, and Table 1b shows the 1-dimensional velocity structure derived for each region.

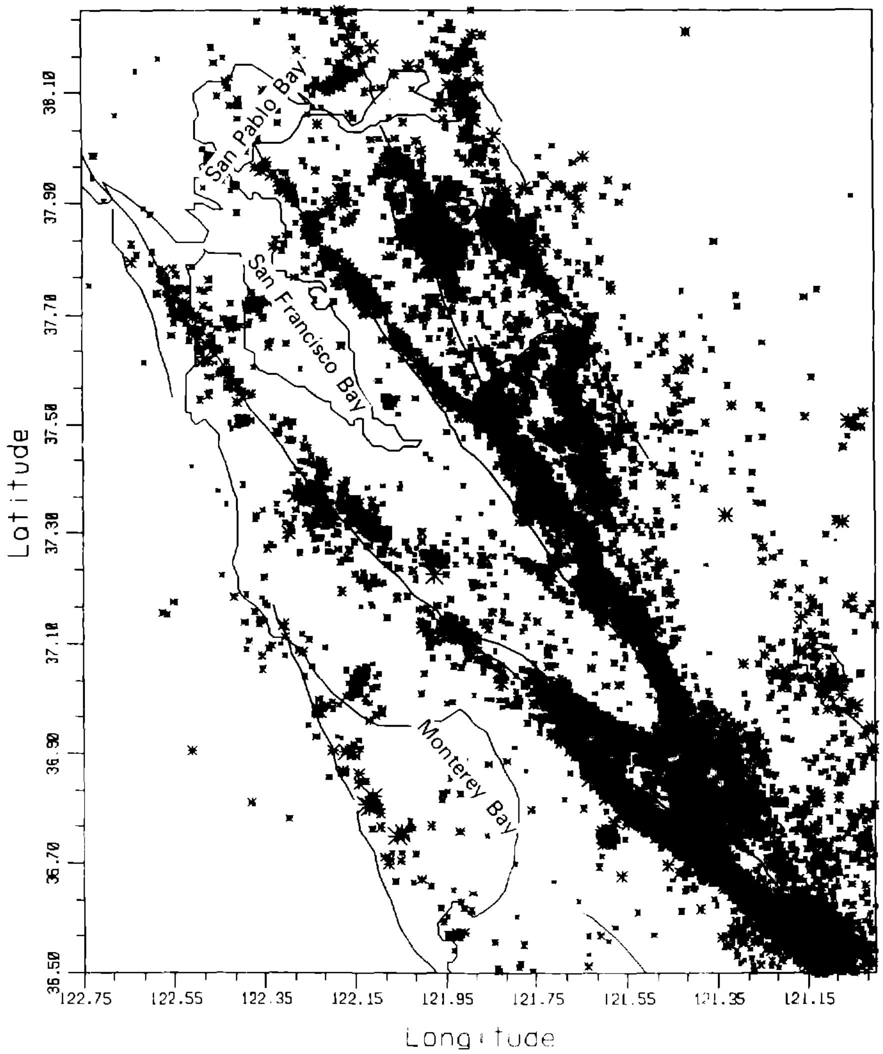

Figure 7. Earthquake epicenters from the USGS CALNET catalog for the time period 1969 through mid-1982.

Events in each subregion were extracted from the larger data set, relocated, and then merged to form a new version of the larger data set. Because of the varying methods used to calculate magnitudes, some discrepancies were found after this relocation had been done. These discrepancies were most acute during the time that the peak velocity magnitude measure had been in use. This resulted from a difficulty in determining accurate gains for the instruments during this time period. Therefore, for the time period 1969 to May 1970, we referred to Lee *et al.* (1972b and 1972c) and corrected our magnitudes to those shown in the catalogs.

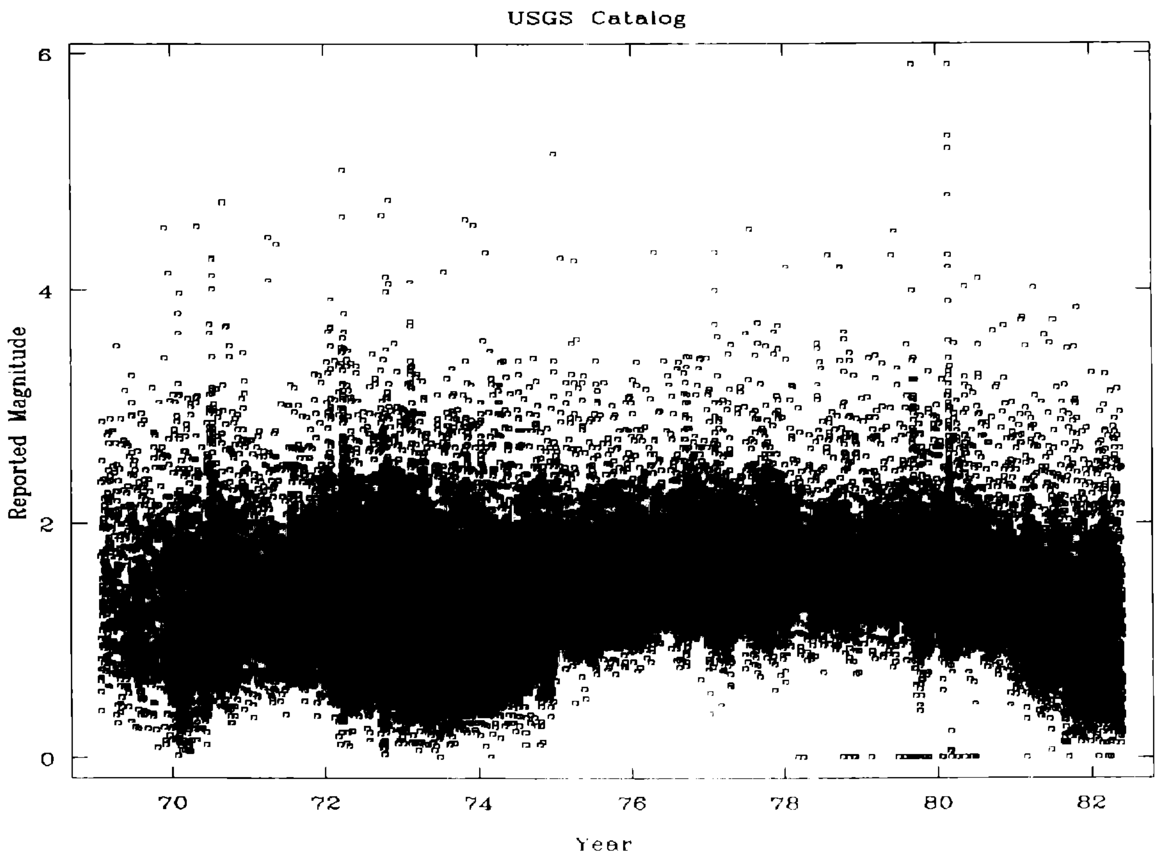

Figure 8. Magnitudes of events from the USGS catalog as plotted in Figure 7. are plotted as a function of time to illustrate the completeness of this data set. The catalog appears to be complete down to M_L 1.6 for the time period Jan. 1, 1969 through December, 1982.

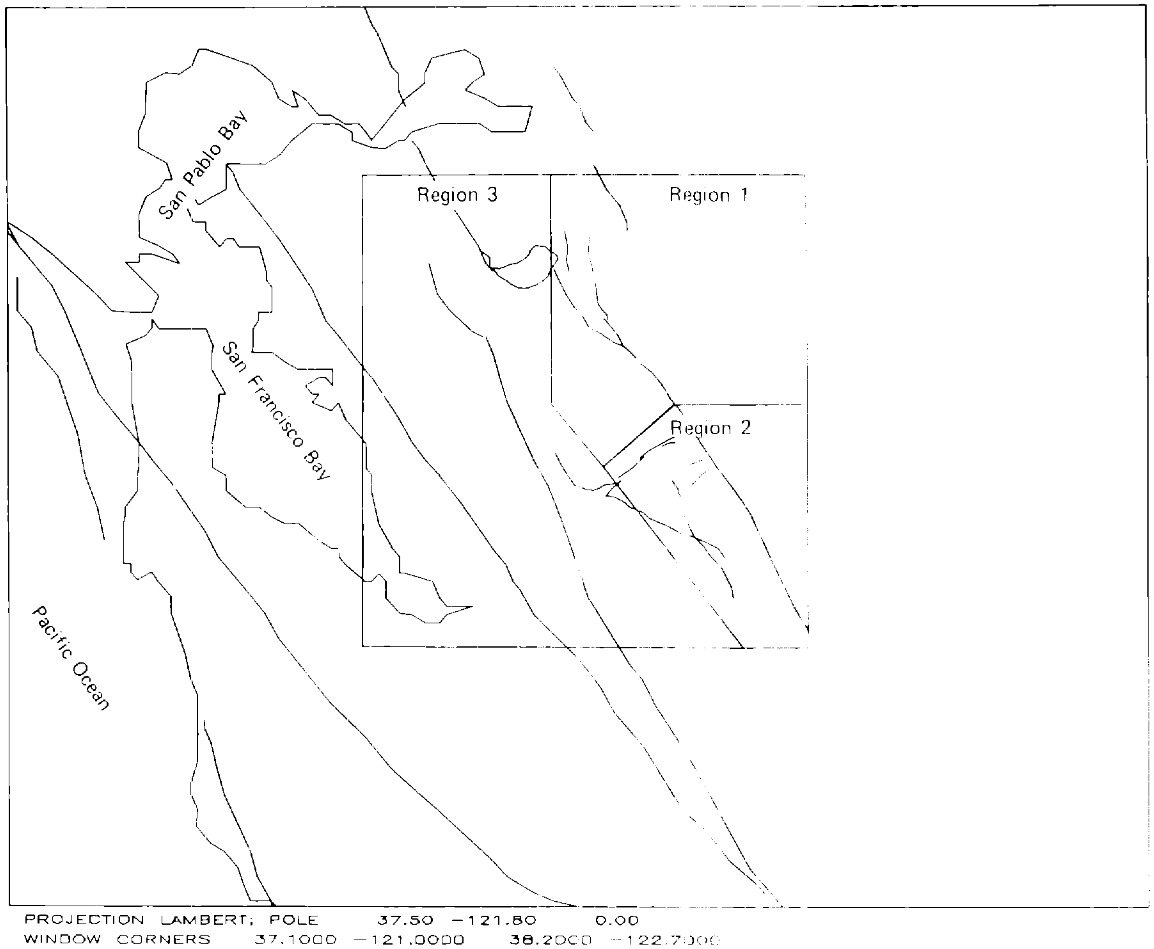

Figure 9. The Livermore Valley region was divided into three smaller regions, and a specific velocity model and set of station corrections was derived for each of these sub-regions. After the earthquakes in each region were relocated using that regional model, all the summary epicenter information was merged to form one data set.

Table 1a. Stations and Delays for Relocations.

Station Name	North Latitude	West Longitude	Elevation (feet)	Delay (s)		
				Region 1	Region 2	Region 3
BCG	36° 42.55'	121° 20.60'	305	0.00		
BJC	36° 32.82'	121° 23.53'	207	0.00		
BPC	36° 33.90'	121° 38.15'	268	0.00		
BSC	36° 37.98'	121° 14.05'	357	0.00		
BSG	36° 24.83'	121° 15.22'	192	0.00		
BRK	37° 52.40'	122° 15.60'	81			
CAC	37° 58.57'	121° 45.62'	74	0.41	0.22	0.60
CAL	37° 27.07'	121° 47.95'	265	-0.10	-0.68	-0.21
CAO	37° 20.96'	121° 31.96'	628	-0.16	-0.85	-1.0
CAI	37° 51.68'	122° 25.77'	223	-0.41	-0.28	
CAD	37° 9.77'	121° 37.45'	244	0.00		
CBW	37° 55.45'	122° 6.40'	221	0.05	0.05	-0.02
CBR	37° 48.97'	122° 3.72'	610	0.17	0.26	0.02
CBS	37° 47.81'	121° 38.77'	279	0.07	0.13	0.10
CCN	37° 47.49'	121° 56.89'	219	0.28	0.55	0.14
CCY	37° 33.10'	122° 5.45'	67	-0.18	-0.31	
CCO	37° 15.46'	121° 40.35'	366	0.00		0.31
CDS	37° 57.98'	122° 15.17'	109	-0.17	0.01	0.27
CDU	38° 1.78'	122° 0.05'	168	0.14		0.05
CDV	37° 33.98'	121° 40.80'	250	-0.36	-0.51	0.40
CDA	37° 43.80'	121° 43.70'	190	0.00	0.27	-0.03
CDO	37° 43.80'	121° 50.12'	198	0.16	0.36	0.19
CFR	37° 41.14'	121° 40.26'	260	0.00	0.08	0.02
CLC	37° 44.28'	122° 3.83'	312	0.17	0.19	0.12
CML	37° 28.64'	121° 39.09'	1076	0.00		0.00
CMN	37° 37.65'	121° 42.50'	245	0.02	-0.16	-0.07
CMC	37° 46.88'	122° 10.55'	90	0.02	-0.03	-0.33
CMJ	37° 31.25'	121° 52.23'	498	0.14	-0.26	0.07
CMO	37° 48.68'	121° 48.15'	792	0.11	0.32	0.12
CMR	37° 35.68'	121° 38.22'	500	-0.38	-0.48	-0.25
CMM	37° 27.34'	121° 29.62'	1117	-0.30	-0.83	-0.30
CMH	37° 21.57'	121° 45.38'	518	0.00		
COS	37° 30.51'	121° 22.44'	1020	-0.77	-0.94	-0.98
CPN	37° 39.01'	121° 51.70'	200	0.42	0.43	0.35

Table 1a. (continued)

Station Name	North Latitude	West Longitude	Elevation (feet)	Delay (s)		
				Region 1	Region 2	Region 3
CPS	37° 41.40'	121° 42.00'	155	0.00	0.19	0.11
CPL	37° 38.25'	121° 57.64'	317	0.12	0.05	-0.04
CRA	37° 46.03'	121° 56.25'	171	0.29	0.58	0.40
CRP	37° 54.75'	121° 54.33'	331	-0.34	-0.19	-0.52
CSA	37° 40.43'	121° 42.16'	215	0.00	-0.20	0.00
CSH	37° 38.88'	122° 2.57'	170	0.00	0.06	-0.12
CST	37° 38.35'	121° 29.89'	205	0.00	-0.18	-0.09
CSC	37° 17.11'	121° 46.35'	128	0.00		1.05
CTF	37° 38.78'	121° 40.35'	295	0.00	-0.19	-0.24
CTL	37° 39.44'	121° 38.63'	458	0.13	-0.32	0.11
CVA	37° 37.12'	121° 45.52'	198	0.00	-0.01	
CVL	37° 37.58'	121° 50.14'	245	0.32	0.38	0.26
CVY	37° 38.66'	121° 49.65'	200	0.42		
CWG	37° 36.35'	121° 45.10'	440	0.00	-0.06	0.10
CYH	37° 33.10'	122° 5.62'	38	0.00		
FOR	36° 47.46'	121° 27.28'	433	0.00		
HAZ	36° 53.08'	121° 35.45'	122	0.00		
HCZ	36° 54.54'	121° 48.02'	30	0.00		
HCB	36° 55.88'	121° 39.63'	219	0.00		
HCR	36° 57.46'	121° 35.01'	241	0.00		
HCA	37° 1.52'	121° 29.02'	332	0.00		
HDL	36° 50.12'	121° 38.64'	204	0.00		
HFE	36° 59.00'	121° 24.09'	323	0.00		
HFH	36° 53.29'	121° 28.13'	101	0.00		
HGW	37° 1.02'	121° 39.20'	133	0.00		
HGS	37° 5.75'	121° 26.83'	778	0.00		
HJG	36° 47.88'	121° 34.43'	171	0.00		
HLT	36° 53.07'	121° 18.49'	183	0.00		
HOR	36° 55.03'	121° 30.46'	98	0.00		
HPL	37° 3.13'	121° 17.40'	152	0.00		
HPR	36° 57.19'	121° 41.70'	94	0.00		
HQR	36° 50.02'	121° 12.76'	536	0.00		
JAL	37° 9.50'	121° 50.82'	244	0.00		0.44
JBG	37° 20.52'	122° 20.34'	158	0.36		
JBL	37° 7.69'	122° 10.08'	792	0.01		
JBZ	37° 1.07'	121° 49.15'	213	0.00		

Table 1a. (continued)

Station Name	North Latitude	West Longitude	Elevation (feet)	Delay (s)		
				Region 1	Region 2	Region 3
JBM	37° 19.09'	122° 9.16'	820	0.13	0.13	
JBC	37° 9.62'	122° 1.57'	660	0.20	0.20	0.48
JCB	37° 6.71'	121° 41.33'	192	0.00		
JEG	37° 30.84'	122° 27.74'	202	-0.32	-0.32	
JEC	37° 3.04'	121° 48.56'	438	0.00		
JHL	37° 6.56'	121° 49.95'	908	0.00		
JLT	37° 21.22'	122° 12.25'	270	0.06	0.06	
JLX	37° 12.11'	121° 59.17'	244	0.04	0.04	
JMG	37° 38.22'	122° 28.43'	201	-0.39	-0.39	
JPR	37° 47.70'	122° 28.43'	107	0.00		-0.45
JPS	37° 11.94'	122° 20.90'	84	-0.01	-0.01	
JPL	36° 58.62'	121° 49.93'	158	0.00		
JPP	37° 15.87'	122° 12.78'	186	0.32	0.32	
JRR	37° 3.27'	121° 43.61'	408	0.00		
JSA	37° 34.95'	122° 25.03'	207	-0.17	0.07	-0.49
JSM	37° 12.74'	122° 10.06'	262	0.00		
JSS	37° 10.17'	121° 55.84'	946	0.00		-0.13
JSG	37° 16.96'	122° 3.00'	198	0.49	-0.01	0.28
JST	37° 12.41'	121° 47.84'	149	0.00		-0.15
JSF	37° 24.31'	122° 10.55'	143	0.08	-0.21	-0.07
JSC	37° 17.07'	122° 7.42'	357	0.00		
JSJ	37° 20.03'	122° 5.48'	122	0.44	0.44	0.67
JTG	37° 1.71'	121° 52.58'	253	0.00		
JUC	37° 0.07'	122° 2.91'	177	0.00		
JWS	37° 25.08'	122° 16.33'	280	0.09	0.13	0.12
LADP	37° 43.80'	121° 43.70'	0	-0.20		-0.20
LAHP	37° 48.99'	121° 43.85'	130	0.00		
LCRP	37° 43.68'	121° 41.13'	0	0.00		0.00
LDVP	37° 35.30'	121° 41.48'	0	0.00		
LFRT	37° 41.14'	121° 40.26'	260	0.02	0.08	0.02
LFFP	37° 41.48'	121° 43.76'	150	0.00		
LFPP	37° 32.80'	121° 40.26'	0	0.00		
LMCP	37° 53.61'	121° 43.19'	0	0.00		0.00
LMTP	37° 48.02'	121° 46.80'	0	0.00		0.00
LRRP	37° 32.85'	121° 41.65'	0	0.00		

Table 1a. (continued)

Station Name	North Latitude	West Longitude	Elevation (feet)	Delay (s)		
				Region 1	Region 2	Region 3
LS3P	37° 40.42'	121° 32.37'	395	0.00		
LTFT	37° 38.78'	121° 40.35'	295	-0.27	-0.19	-0.27
LVA1	37° 50.30'	121° 38.43'	0	0.34	0.34	0.50
LVFP	37° 50.95'	121° 38.99'	60	0.50		0.50
LVVR	37° 45.67'	121° 44.10'	0	-0.01	-0.01	0.05
LWGT	37° 36.35'	121° 45.10'	440	0.27	-0.06	0.27
MTH	37° 20.50'	121° 38.50'	0	0.00		
MBF	37° 40.71'	120° 21.80'	309	-1.80		
MCU	37° 58.36'	120° 37.02'	336	-1.50		
MNH	38° 8.75'	120° 48.82'	219	-1.50		
MRF	38° 14.72'	120° 31.24'	799	-1.10		
MST	37° 54.27'	120° 24.29'	366	-1.50		
NBR	38° 15.65'	122° 32.99'	137	0.00		
NFI	37° 41.90'	123° 1.07'	0	0.00		
NGV	38° 16.84'	122° 12.89'	257	0.00		
NHM	38° 9.28'	121° 48.02'	65	0.96	0.74	0.62
NLN	38° 9.15'	122° 42.75'	120	0.00		
NOL	38° 2.50'	122° 47.62'	37	0.00		
NSP	38° 10.96'	122° 27.20'	88	0.00		
PGH	35° 49.86'	120° 21.17'	433	0.00		
PPF	35° 52.91'	120° 24.81'	469	0.00		
PTY	35° 56.73'	120° 28.45'	552	0.00		

Table 1b. Velocity models for regions 1,2, and 3

REGION 1			REGION 2		
Layer	P-velocity (km/s)	Depth (km)	Layer	P-velocity(km/s)	Depth(km)
1	3.125	0.0-1.0	1	3.088	0.0-1.0
2	4.019	1.0-2.0	2	4.250	1.0-2.0
3	4.309	2.0-3.0	3	4.572	2.0-4.0
4	4.509	3.0-4.0			
5	4.879	4.0-5.0	4	4.863	4.0-5.0
6	5.135	5.0-7.0	5	5.044	5.0-7.0
7	5.657	7.0-12.0	6	5.473	7.0-12.0
8	6.420	12.0-25.0	7	6.399	12.0-25.0
9	7.736	Below 25.0	8	7.750	Below 25.0

REGION 3

Layer	P-velocity (km)	Depth (km/s)
1	3.4	0.0-1.0
2	4.0	1.0-2.0
3	4.6	2.0-3.0
4	4.8	3.0-4.0
5	5.0	4.0-5.0
6	5.1	5.0-6.0
7	5.3	6.0-7.0
8	5.6	7.0-12.0
9	5.9	12.0-17.0
10	6.2	17.0-25.0
11	8.0	Below 25.0

Even after correcting the early magnitudes, we had some question about the sources of the magnitudes given in the catalogs of Lee *et al.* (1972b and 1972c). Therefore, we used the reported M_L from UCB for all events larger than magnitude 2.75 in our fourth data set. The events which fall into this category are shown in Figure 10. The changes in the locations due to the relocation, while sometimes affecting the zone to which an event would be assigned, were not large enough to materially affect the UCB estimate of M_L. The final data set, consisting of recalculated epicenters with magnitudes greater than 12.75 corrected to the UCB M_L's, is shown in Figure 11, and the stationarity in Figure 12. The magnitudes of events larger than 2.75 have been corrected using UCB-reported M_Ls. Smaller magnitudes are estimated using the coda length procedure of Lee *et al.* (1972a).

Methodology - Least-Squares Method (LSM)

Each earthquake catalog was divided into cells which contained all earthquakes in a certain magnitude increment dM. Least-squares estimates of a- and b-values were calculated by finding the best fitting coefficients a and b, as in Eq. (1), which minimized the

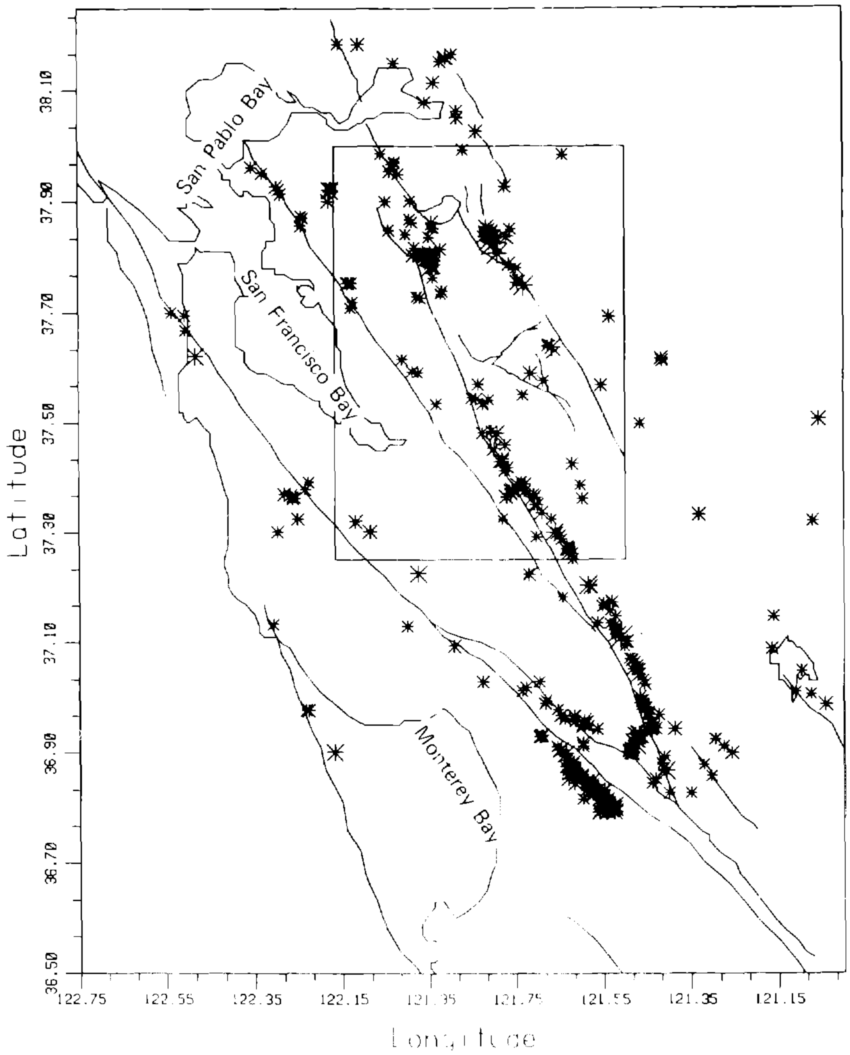

Figure 10. All events from the combined catalogs with $M_L \geq 2.75$ are shown. All events which were relocated and whose magnitudes were corrected using the UCB catalog are shown within the box in this figure. None of the relocation vectors were large enough to justify modifying the reported magnitude to correct for station-to-event distance.

variance

$$E = \sum^{N_{i=1}} \left[\log\left(n_i\right) - a + bM_i\right], \tag{2}$$

where n_i is the number of earthquakes between magnitude M_i and $M_i + dM$. The cell size dM was chosen to be 0.2 magnitude units. Smaller cell sizes were also tested to verify that the values of a and b were independent of cell size.

Using the least squares formulation gives values for a and b as follows:

$$a = \frac{1}{N} \sum^{N_{i=1}} \log(n_i) + \frac{b}{N} \sum^{N_{i=1}} M_i, \tag{3}$$

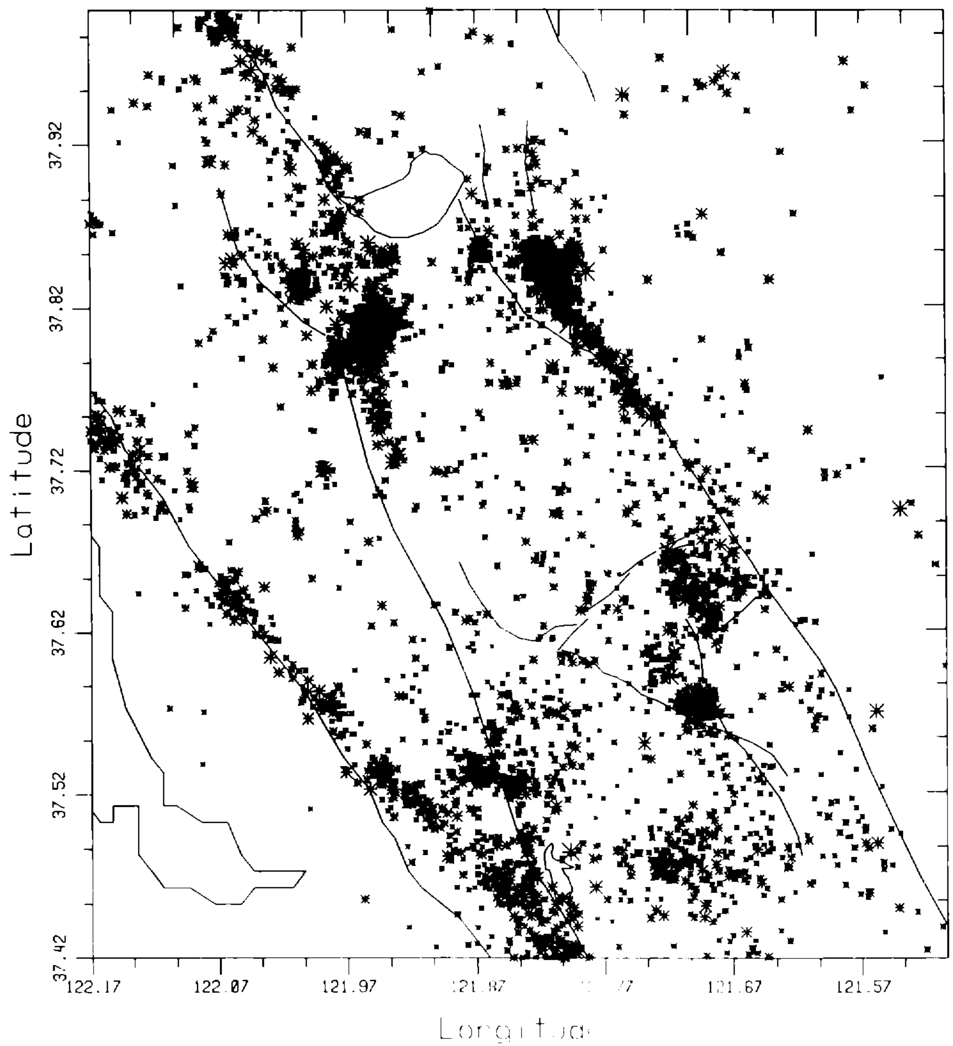

Figure 11. Epicenters for earthquakes derived by relocations using the velocity models and station corrections shown in Table 1a and 1b, and phase arrival data collected by both the USGS CALNET and the LLNL Local Seismic Networks. The magnitudes of events larger than 2.75 have been corrected using UCB-reported M_L's. Smaller magnitudes are estimated using the coda length procedure of Lee, *et al.* (1972a).

$$b = \frac{\dfrac{\left\{\sum^{N_{i=1}} \log(n_i)\right\}\left\{\sum^{N_{i=1}} M_i\right\}}{N\sum^{N_{i=1}} M_i^2} - \dfrac{\sum^{N_{i=1}} \log(n_i) M_i}{\sum^{N_{i=1}} M_i^2}}{\dfrac{\{1-(\frac{1}{N})\}\left\{\sum^{N_{i=1}} M_i\right\}^2}{\sum^{N_{i=1}} M_i^2}}, \tag{4}$$

where n_i is the number of earthquakes between magnitude M_i and M_{i+1} (that is, in the i^{th} cell), and N is the number of cells.

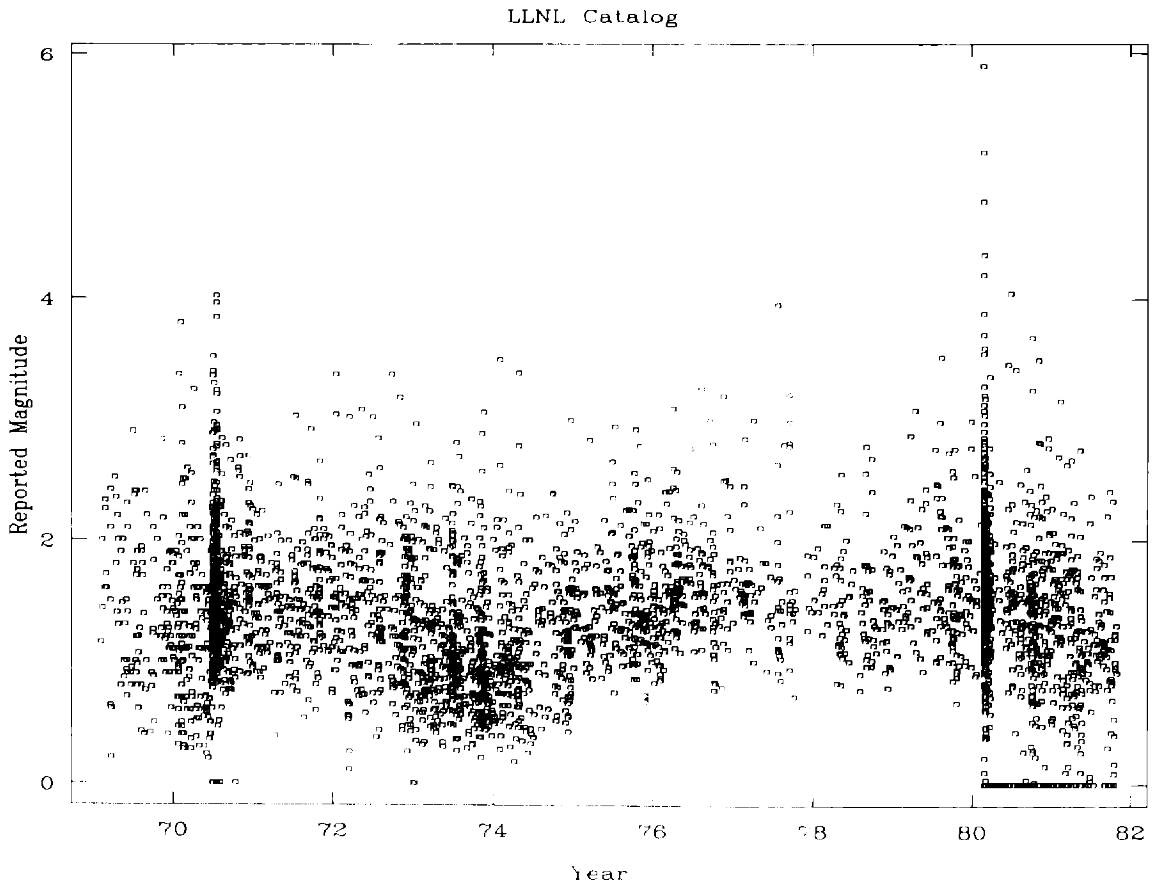

Figure 12. Magnitudes of events from the LLNL catalog as plotted in Figure 11. are plotted against time to illustrate the completeness of this dataset. The catalog appears to be complete down to M_L 1.4.

Methodology - Maximum Likelihood Method (MLM)

Utsu (1965) derived an estimator for the b-value given by

$$b = \frac{\log_{10}(e)}{\bar{M} - M_{min}}, \tag{5}$$

where $\bar{M}$ is the mean of the sample population and M_{min} is the minimum magnitude in that population. Aki (1965) showed that this estimator was the maximum-likelihood estimate for b and that the 95% confidence limits of this estimate could be derived from

$$\frac{(1 - d_\epsilon/\sqrt{n})}{\sum^{n_1} M_i/n - M_0} \leq b' \leq \frac{(1 + d_\epsilon/\sqrt{n})}{\sum^{n_1} M_i/n - M_0}, \tag{6}$$

where $b' = b/\log(\epsilon)$ and $d_\epsilon = 1.96$ for $\epsilon = 95\%$. This result was derived using the central limit theorem, assuming large numbers of earthquakes in the sample. Utsu (1966) then expanded upon this work and derived an exact representation for the probability density function for b for any size population. Utsu's results agreed with Aki's for sample populations greater than 50, but were extended down to sample sizes as small as 7. Using Utsu's results, one can estimate the significance of any difference in b-value between two samples by comparing the ratio of the two b-values to the F-value (at a given confidence level) which has degrees of freedom equal to those for each b-value estimate. Values of a were determined, once the MLM estimate of the b-value was made, using Eq. (2). In this case, b was fixed at the MLM value, and the best fitting a was solved for, given the slope b.

Interpretation

Both least-squares and maximum-likelihood estimators for b-values were used in deriving b-values for all zones. In cases in which many earthquakes were in a set of data for a zone the results were quite comparable. When the distribution became slightly abnormal or only a few earthquakes were included, the maximum-likelihood estimator for b-value seemed to be much more robust. For this reason, we have used the maximum-likelihood estimator for b-values and have used the least-squares estimator for determining the a-value. As a check on our methods, we considered several subdivisions of the Pfluke and Steppe Calaveras zone, and calculated both a- and b-values using USGS epicenters for the period 1969-1972. Our data set contains nine more earthquakes than that of Pfluke and Steppe, but our a- and b-values agree with theirs. Table 2 gives the results for each of the source zones. Detailed plots for each source zone and catalog combination are in the Appendix.

Table 2. *a*- and *b*-values derived for all combinations of hazard zones and catalogs.

Source Zone	M_0	N	*b*-value	95% lim.	*a*-value	Catalog
Z1-Hayward	2.5	121	0.953	0.170	4.656	CDMG
Z1	2.5	184	0.972	0.141	4.822	UCB
Z1	1.6	322	0.903	0.099	3.881	USGS
Z1*	1.4	221	0.989	0.130	3.702	LLNL
Z2-Calaveras	2.5	204	0.785	0.108	4.235	CDMG
Z2	2.5	415	0.838	0.081	4.694	UCB
Z2	1.6	1286	0.950	0.052	4.700	USGS
Z2*	1.4	273	0.928	0.110	3.778	LLNL
Z3-Diablo	2.5	44	1.435	0.424	5.791	CDMG
Z3	2.5	57	1.244	0.323	5.220	UCB
Z3	1.6	200	1.174	0.163	4.383	USGS
Z3	1.4	249	1.132	0.141	4.039	LLNL
Z4-Greenville	2.5	11	0.937	0.554	3.457	CDMG(00-74)
Z4	2.5	17	0.879	0.418	3.518	UCB(10-79)
Z4	1.6	84	1.139	0.244	3.637	USGS(69-79)
Z4	1.6	345	0.910	0.663	4.733	USGS(69-82)
Z4	1.4	12	0.875	0.304	3.089	LLNL(69-79)
Z4	1.6	478	0.754	0.087	4.355	LLNL(69-82)
Z5-Las Positas	2.5	1				CDMG
Z5	2.5	4	0.914	0.896	3.041	UCB
Z5	1.6	9	1.563	1.021	3.573	USGS
Z5	1.4	30	0.941	0.337	2.754	LLNL
Z6-Verona	2.5	5				CDMG
Z6	2.5	5				UCB
Z6	1.6	8				USGS
Z6	1.4	13	1.266	0.688	2.917	LLNL
Z7-Liv.Valley	2.5	16	0.675	0.331	2.955	CDMG
Z7	2.5	20	0.736	0.323	3.204	UCB
Z7	1.6	18	1.301	0.601	3.790	USGS
Z7	1.4	29	1.521	0.553	3.635	LLNL
Z8-Danville	2.5	61	0.874	0.219	4.018	CDMG
Z8	2.5	79	1.086	0.240	4.631	UCB
Z8	1.6	435	0.888	0.084	4.055	USGS
Z8	1.4	489	0.842	0.075	3.787	LLNL
Z9-Concord	2.5	28	0.715	0.265	3.292	CDMG
Z9	2.5	36	0.774	0.253	3.567	UCB
Z9	1.6	98	0.970	0.192	3.500	USGS
Z9	1.4	104	0.828	0.075	3.787	LLNL

* The LLNL catalog for zones Z1 and Z2 covers a smaller area than the other catalogs.

In comparing b-values and 95% confidence limits for different catalogs within each zone, it is clear that the resulting b-values are substantially in agreement in each zone even though some of the estimates have large 95% confidence limits. Meaningful differences at the 95% confidence level exist only for zone 4 between the b-values estimated from data for years 1969-1979 from the USGS catalog and the b-value estimated from the LLNL catalog for years 1969-1982. This difference is caused by peculiarities of the Livermore earthquake sequence of 1980; these peculiarities are included in the LLNL data set for 1969-1982, but are not in the USGS data set for 1969-1979. Even so, the differences between b-values estimated from the two versions of either the USGS or LLNL catalogs are not meaningful at the 95% confidence level. These effects are due to differences between the character of earthquakes which were located shallower than 8 km compared to those with hypocenters deeper than 8 km. The shallower events of this sequence have predominately north-south striking strike-slip mechanisms and appear to be associated with north-south striking faults such as the Marsh Creek Fault while the deeper events have predominately north-northwest striking strike-slip mechanisms that are in agreement with other activity located further to the south on the Greenville Fault (see depth cross sections in Cockerham and Scheimer, 1982). In zones 1 and 2 the smallest confidence limits were obtained with the USGS data set due to the larger size of these regions and, hence, numbers of events located within them in the USGS catalog compared to the LLNL catalog. For all other zones except the Livermore Valley zone, the LLNL b-value estimates have smaller 95% confidence limits than those from the other catalogs. In the Livermore Valley zone, a broad zone of typically diffuse seismicity, there are possibly several different faults producing the reported activity. The mixing of these different sources may well be the cause of the larger confidence limits in this case. Events located within this region from the UCB and CDMG catalogs are mostly locations prior to 1969 and are most probably events on the Calaveras or Greenville Faults which have been located with poor enough accuracy to place them in the Livermore Valley region.

Conclusions

We have used the maximum-likelihood method derived by Utsu to calculate $b-$values for nine seismogenic zones in the eastern San Francisco Bay region. Similarly, using these $b-$values, we have used a least-square method to calculate the corresponding $a-$values for each of these zones. There is moderately wide variation in the calculated $b-$values for each zone, depending on the seismicity catalog. Comparison of the b-values with the smallest confidence limits from each of the different zones (with the exception of zone 7 for which we consider the LLNL estimate to be the best for reasons described in the previous paragraph) leads us to recognize that most of the zones (1, 2, 4, 5, 6, 8, and 9) have b-values which are not meaningfully different. We find that seismicity in the two large diffuse zones, zones 3 and 7, are distinctly higher than in the other zones.

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Appendix A

The calculation of each of the b-values in Table 2 were based on the datasets reproduced in the following figures. For each combination of data source and seismogenic zone, we have plotted the epicenters of the earthquakes, the density distribution of magnitudes and the cumulative magnitude distribution. The line corresponding to b-value reported in Table 2 is also drawn on the cumulative plot.

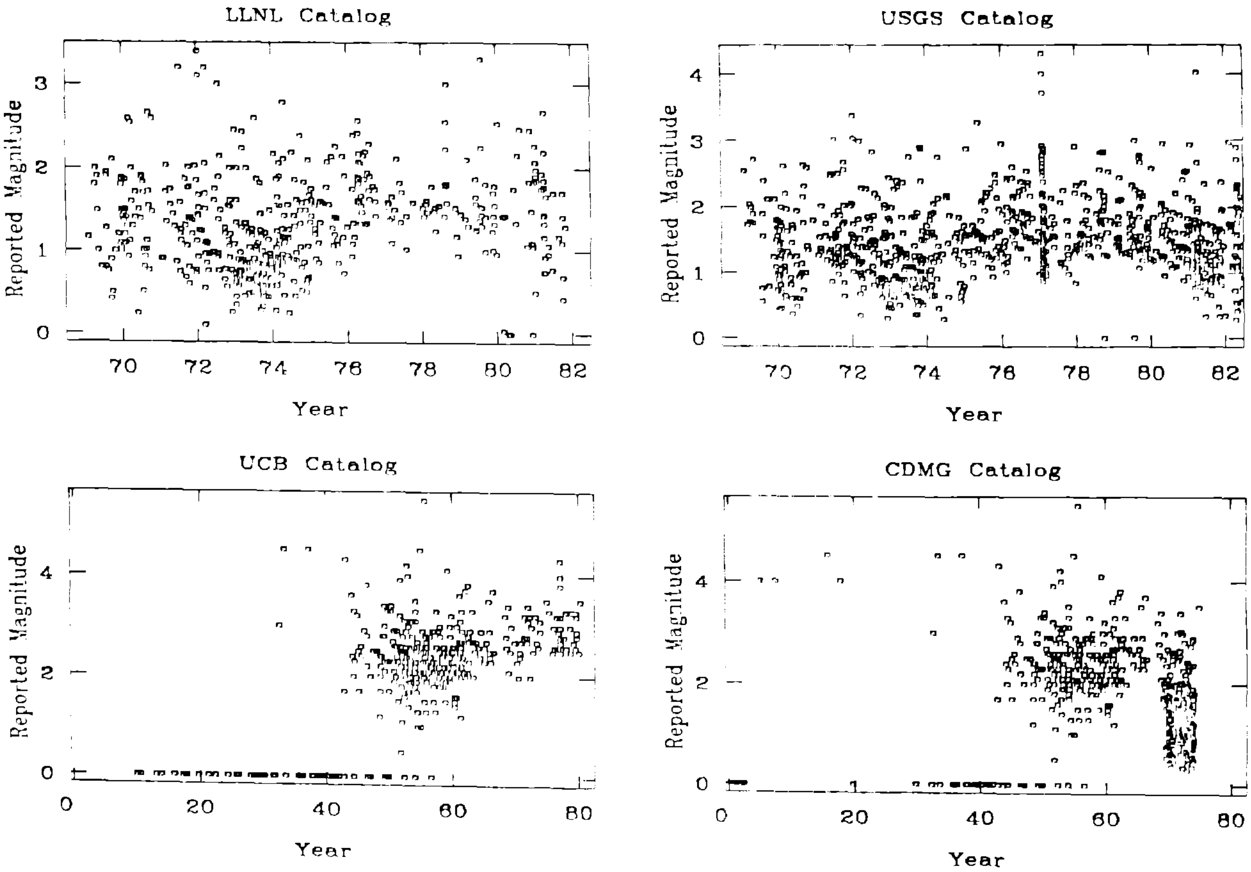


Figure A1. HZ1 - Hayward Fault - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

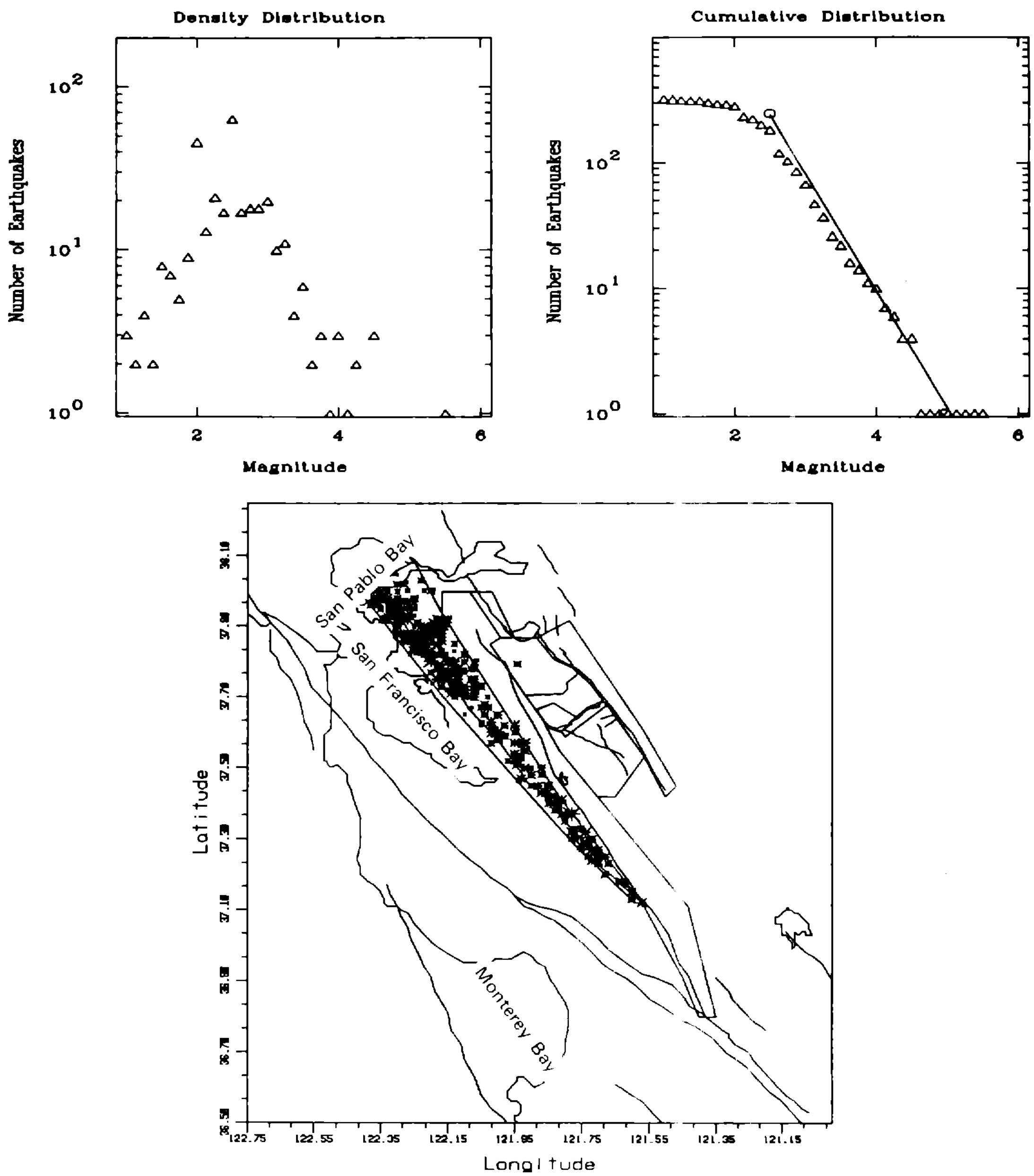


Figure A2. Hazard zone HZ1, Hayward Fault, using the UCB earthquake catalog. The b-value is 0.972 for $M_L \geq 2.50$

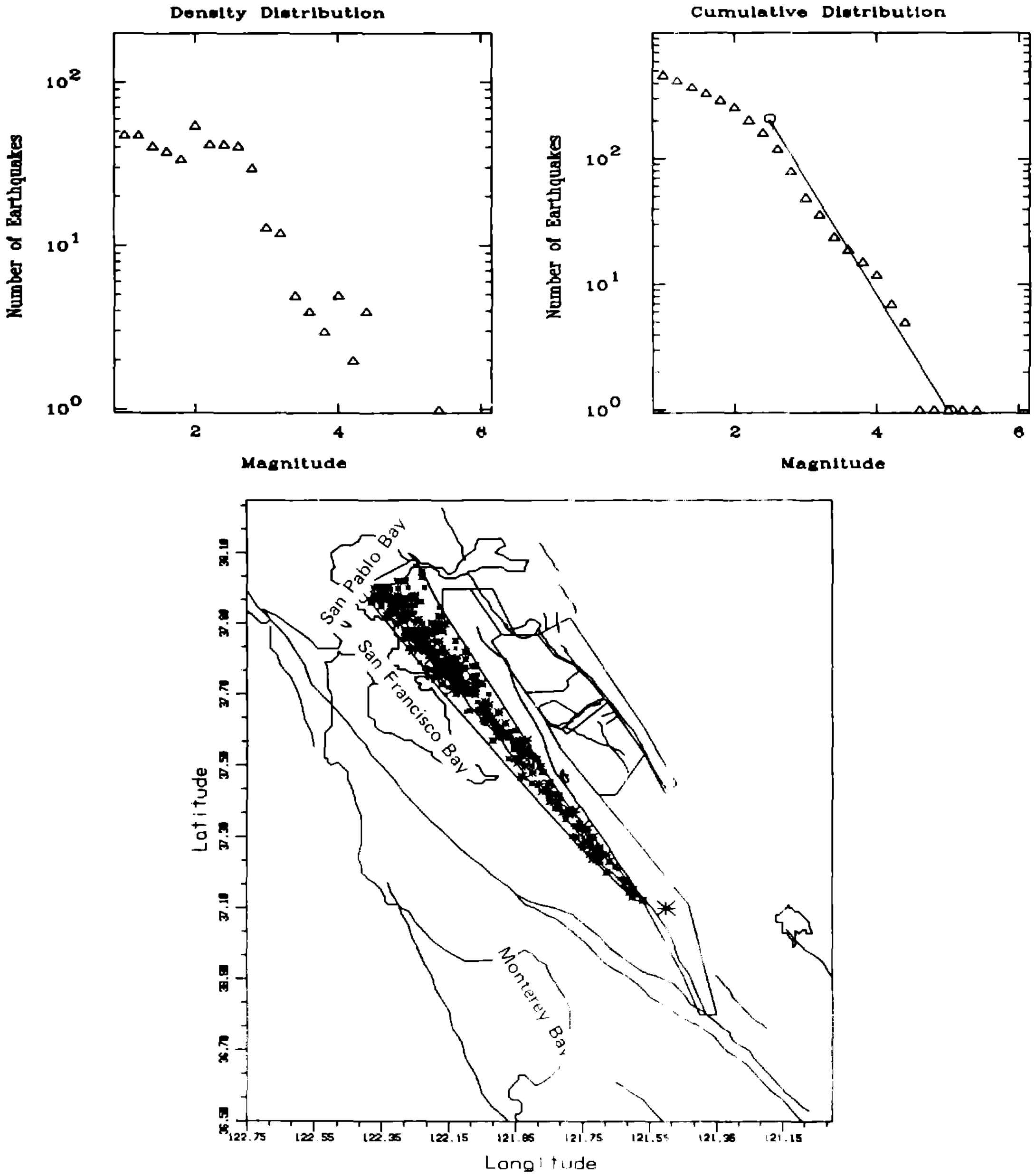


Figure A3. Hazard zone HZ1, Hayward Fault, using the CDMG earthquake catalog. The b-value is 0.953 for $M_L \geq 2.50$

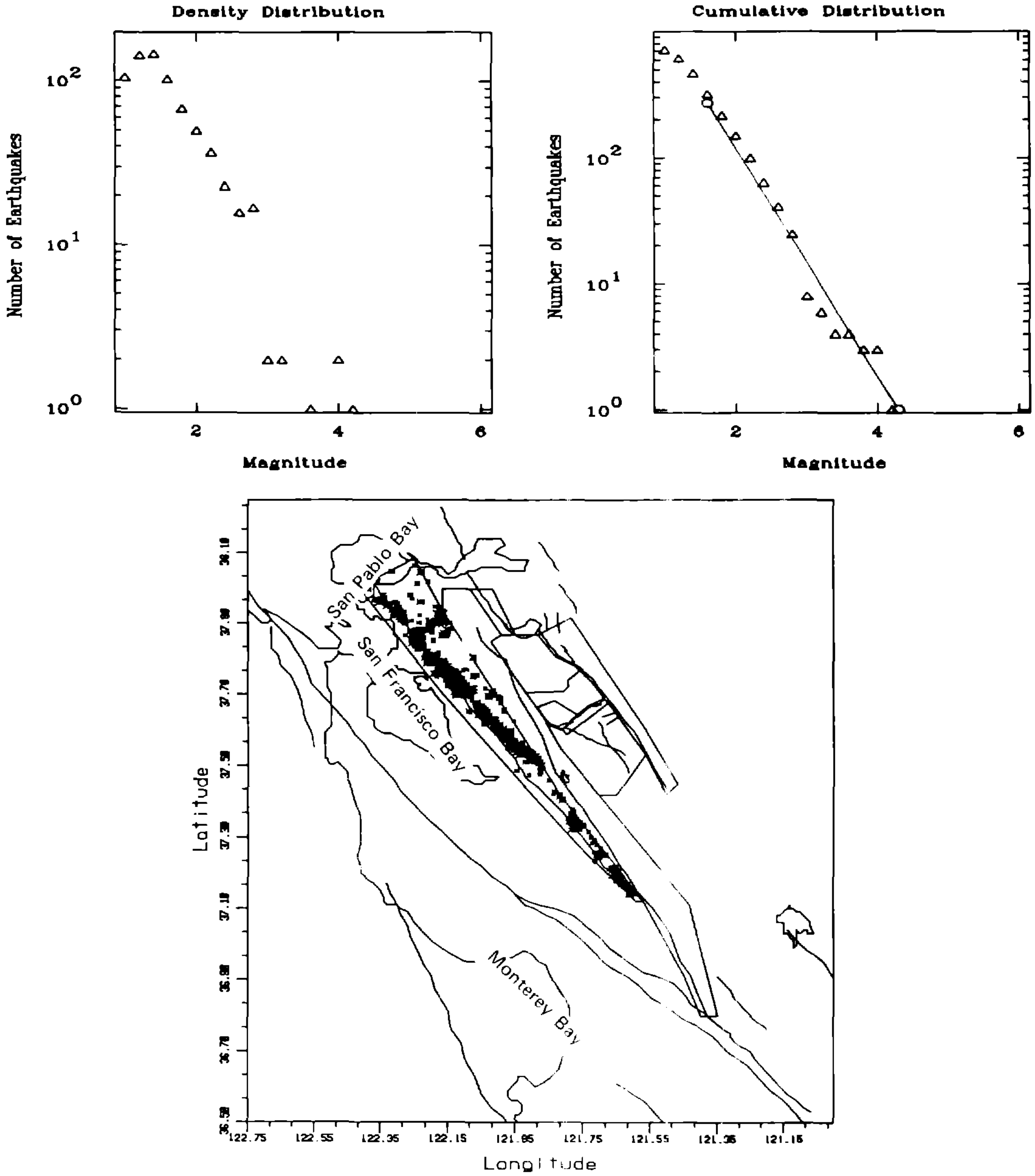


Figure A4. Hazard zone HZ1, Hayward Fault, using the USGS earthquake catalog. The b-value is 0.903 for $M_L \geq 1.60$

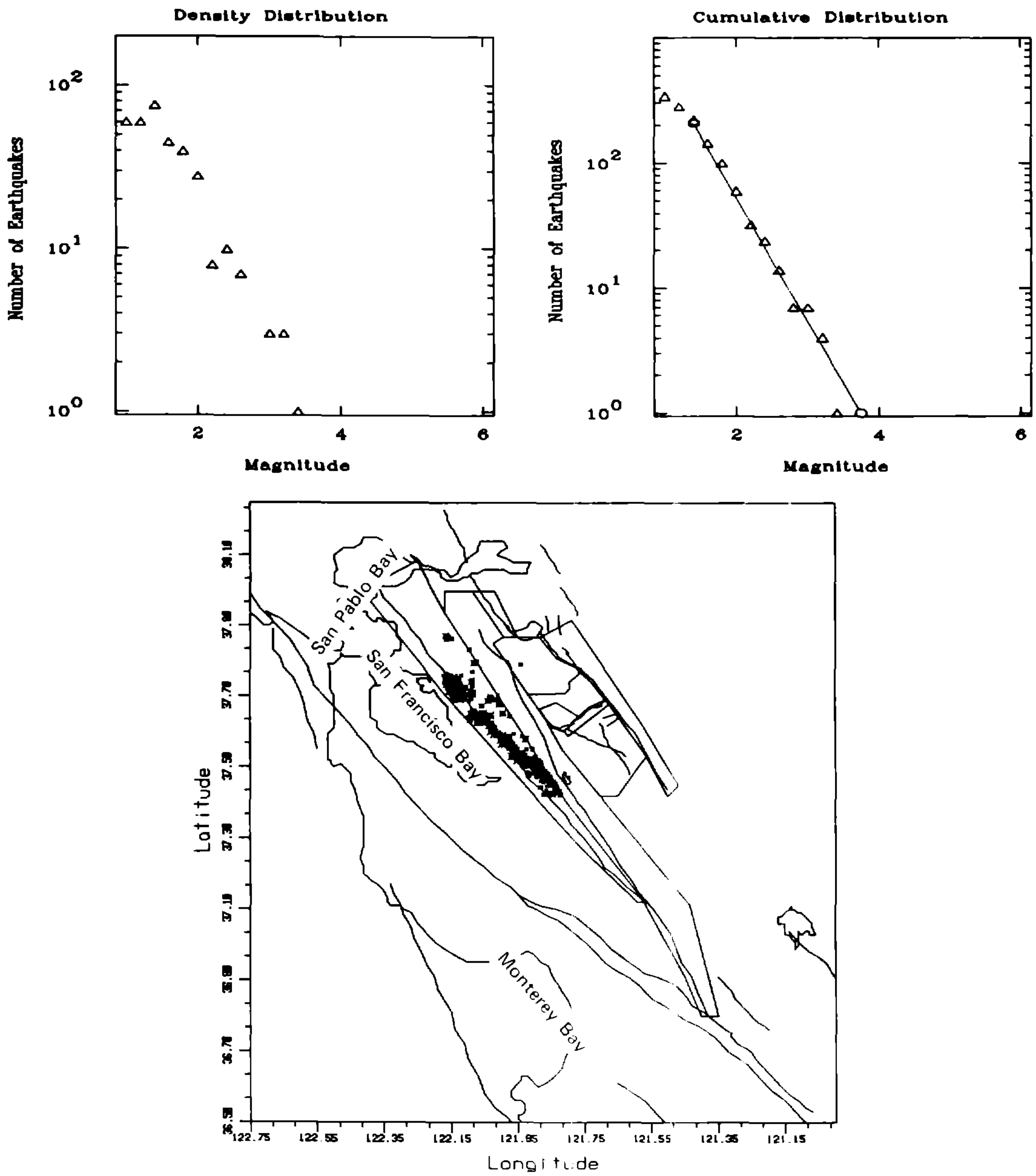


Figure A5. Hazard zone HZ1, Hayward Fault, using the LLNL earthquake catalog. The b-value is 0.989 for $M_L \geq 1.40$

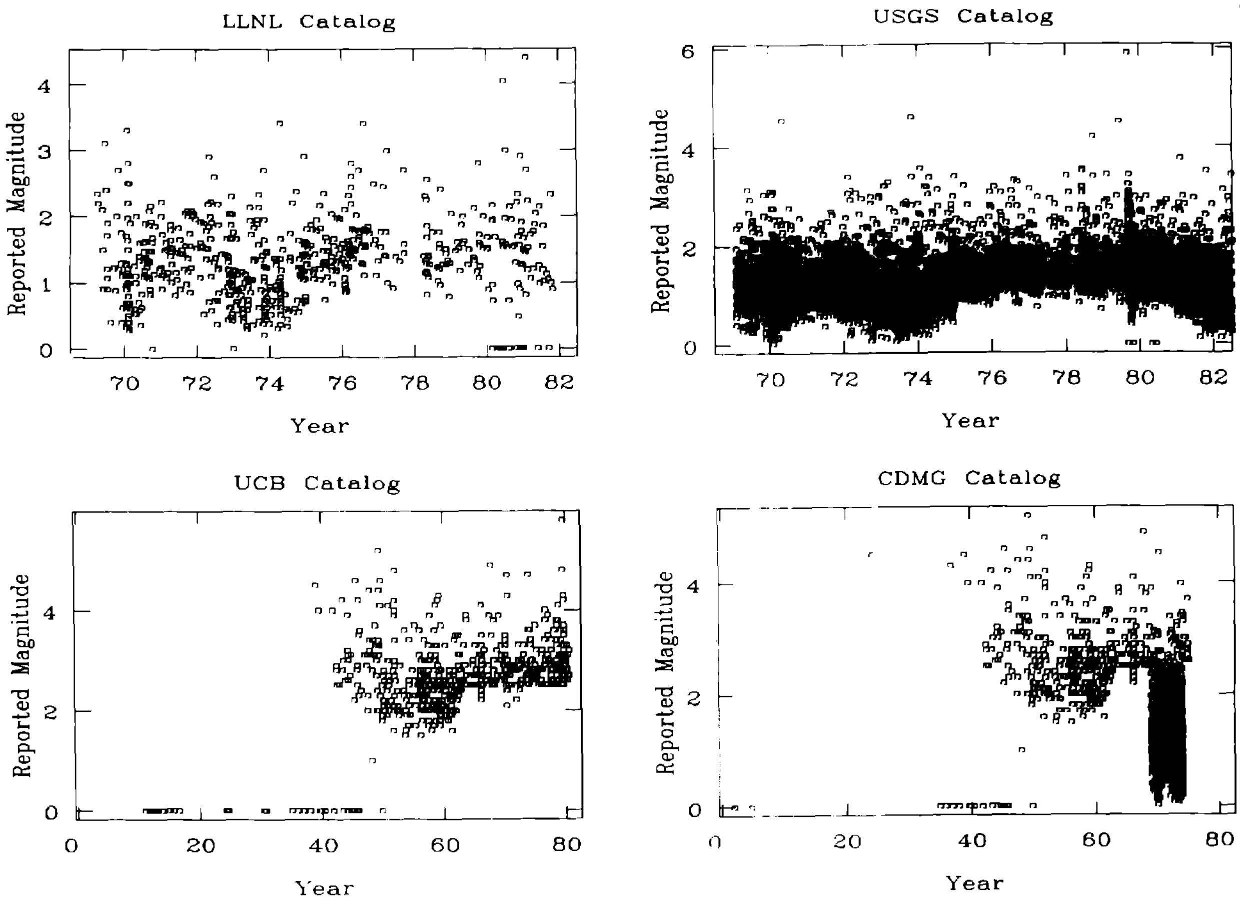


Figure A6. HZ2 - Calaveras Fault - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

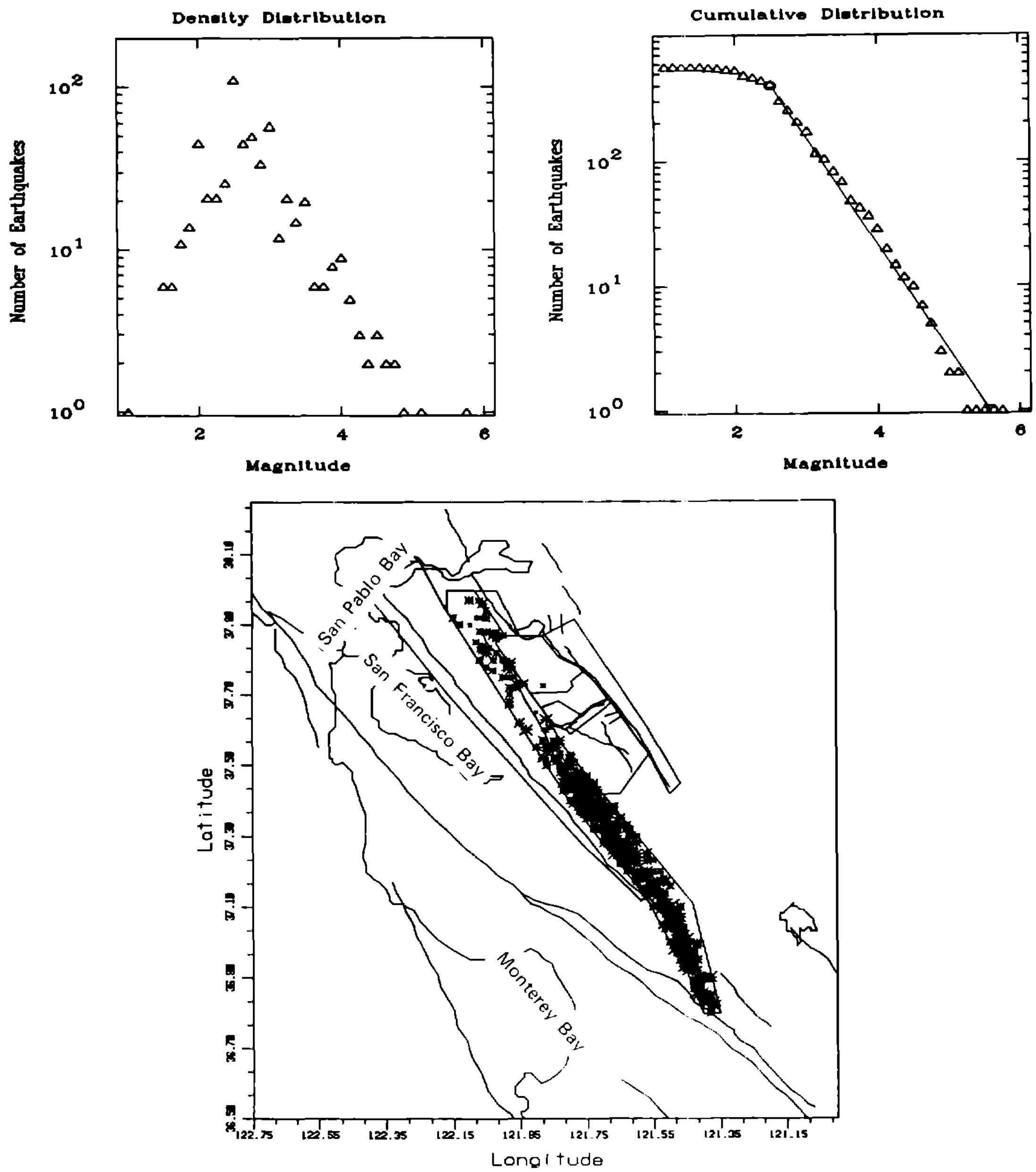


Figure A7. Hazard zone HZ2, Calaveras Fault, using the UCB earthquake catalog. The b-value is 0.833 for $M_L \geq 2.50$

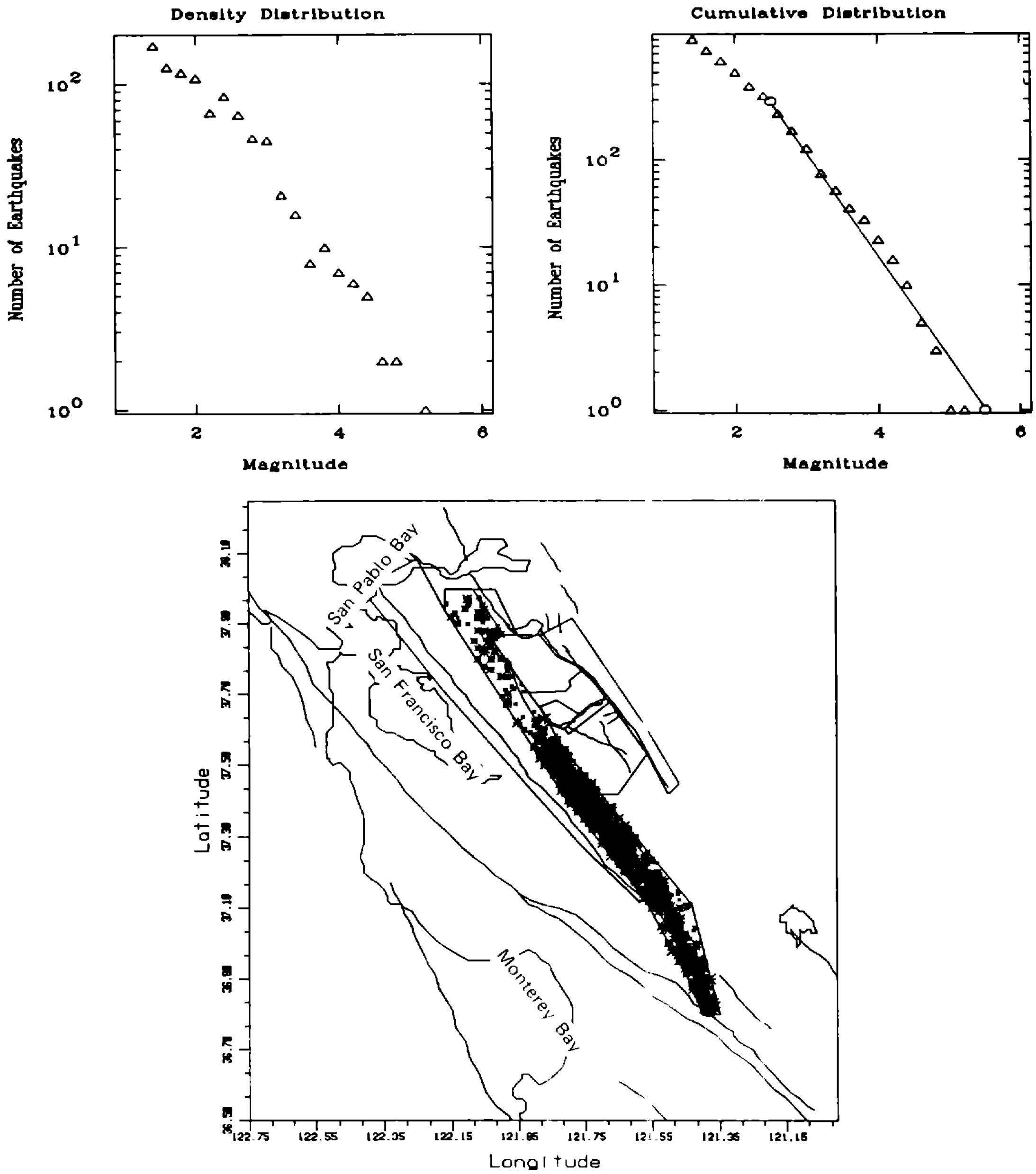


Figure A8. Hazard zone HZ2, Calaveras Fault, using the CDMG earthquake catalog. The b-value is 0.785 for $M_L \geq 2.50$

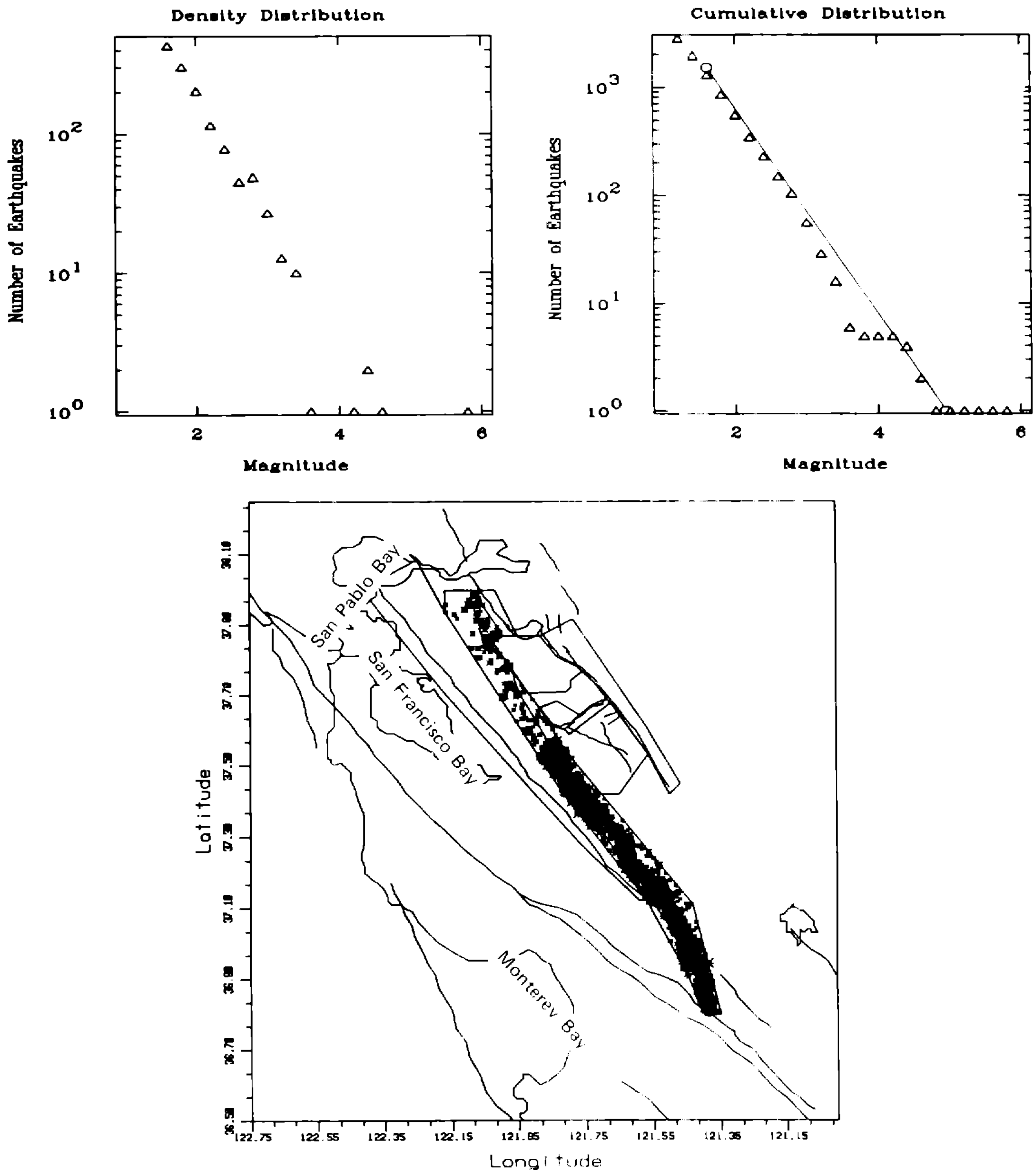


Figure A9. Hazard zone HZ2, Calaveras Fault, using the USGS earthquake catalog. The b-value is 0.950 for $M_L \geq 1.60$

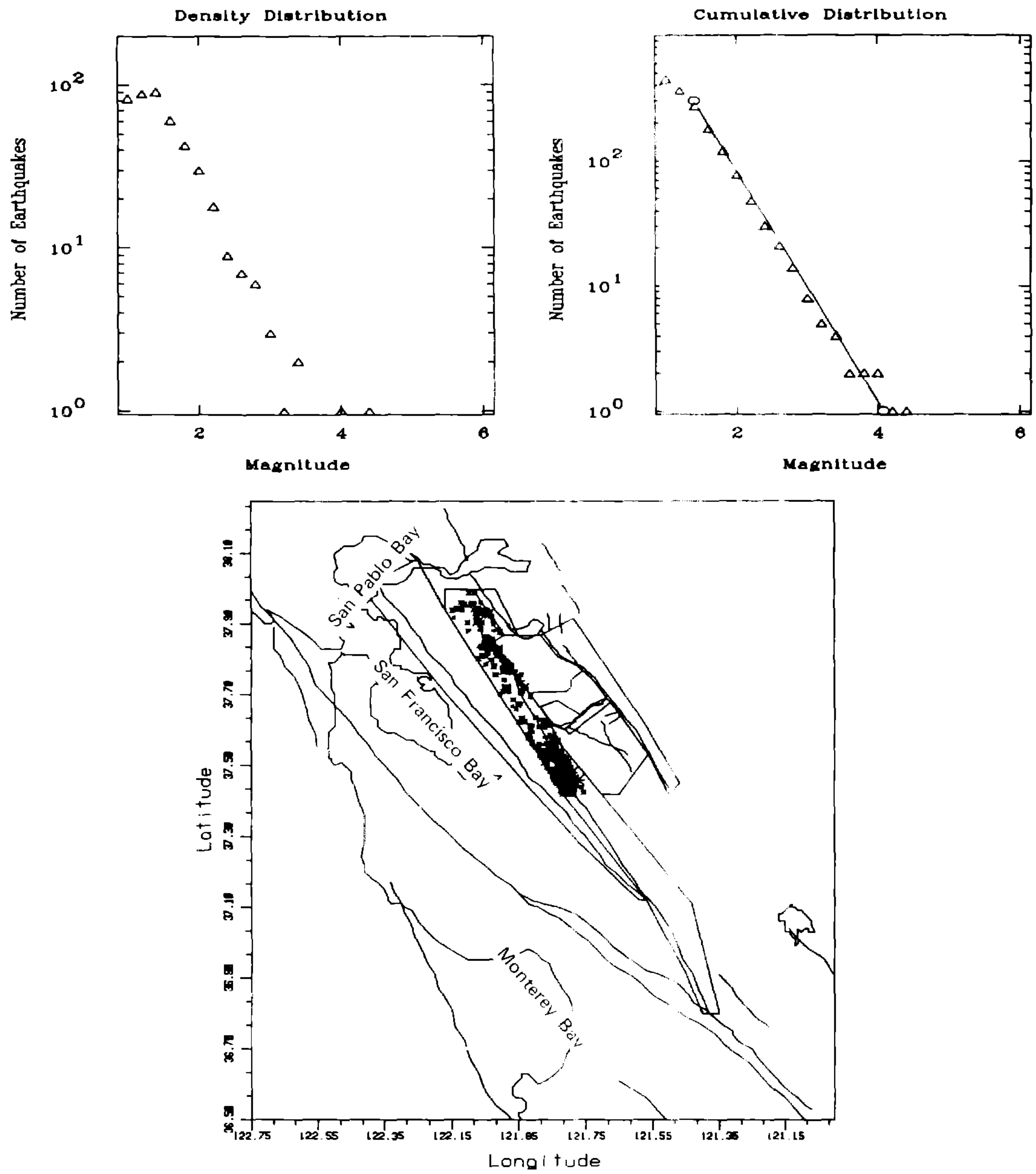


Figure A10. Hazard zone HZ2, Calaveras Fault, using the LLNL earthquake catalog. The b-value is 0.928 for $M_L \geq 1.40$

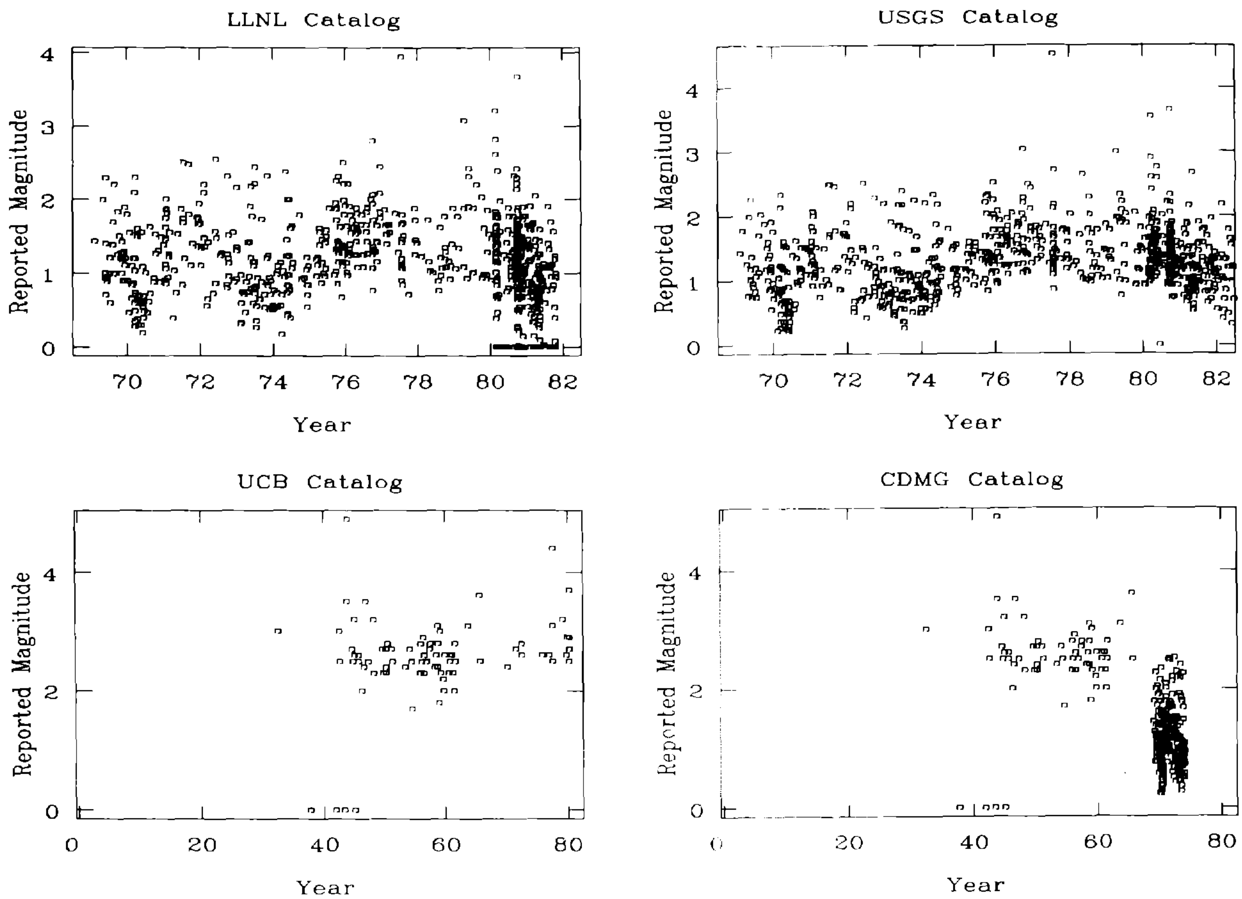


Figure A11. HZ3 - Diablo Region - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

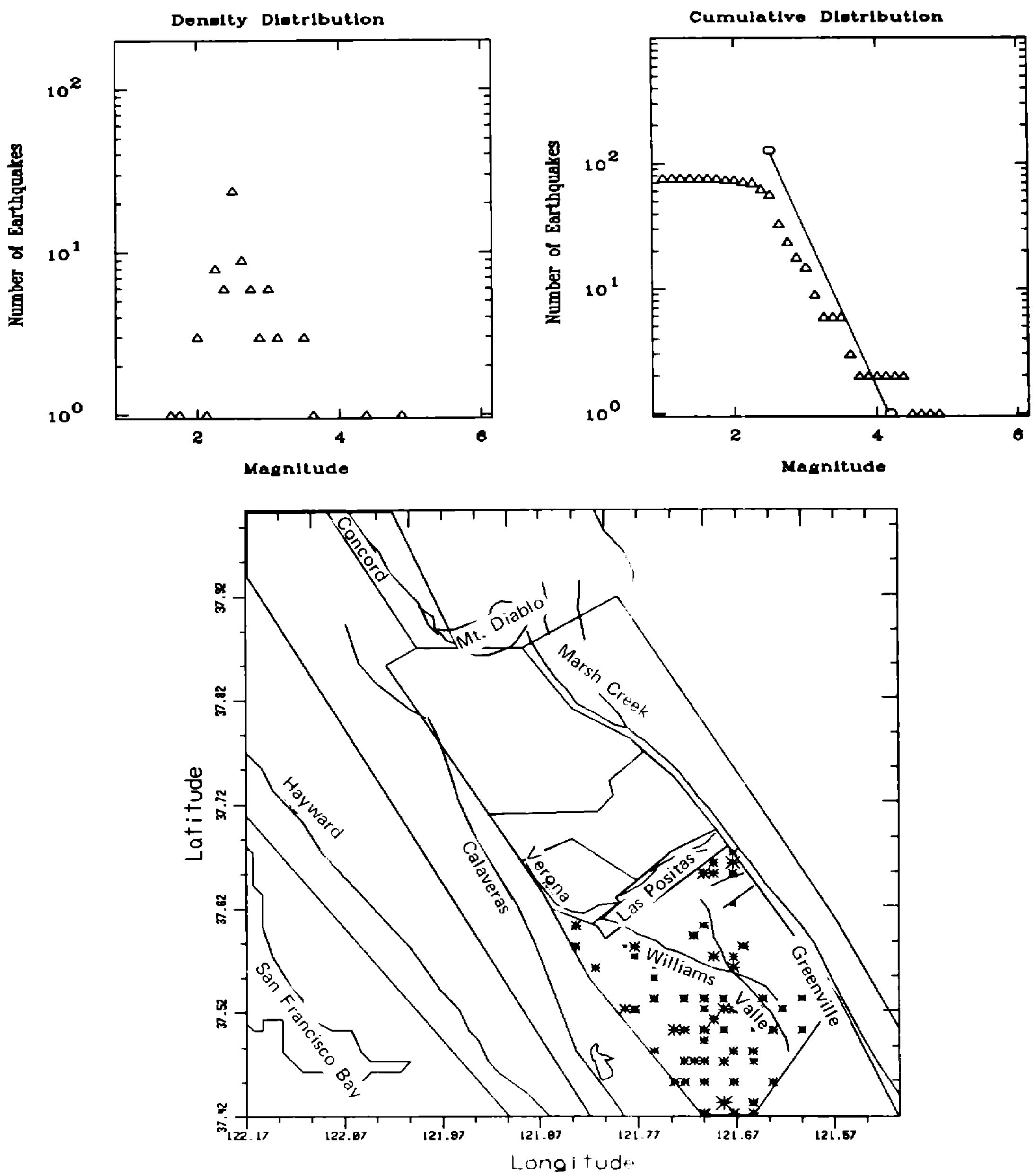


Figure A12. **Hazard zone HZ3, Diablo Region, using the UCB earthquake catalog. The b-value is 1.244 for** $M_L \geq 2.50$

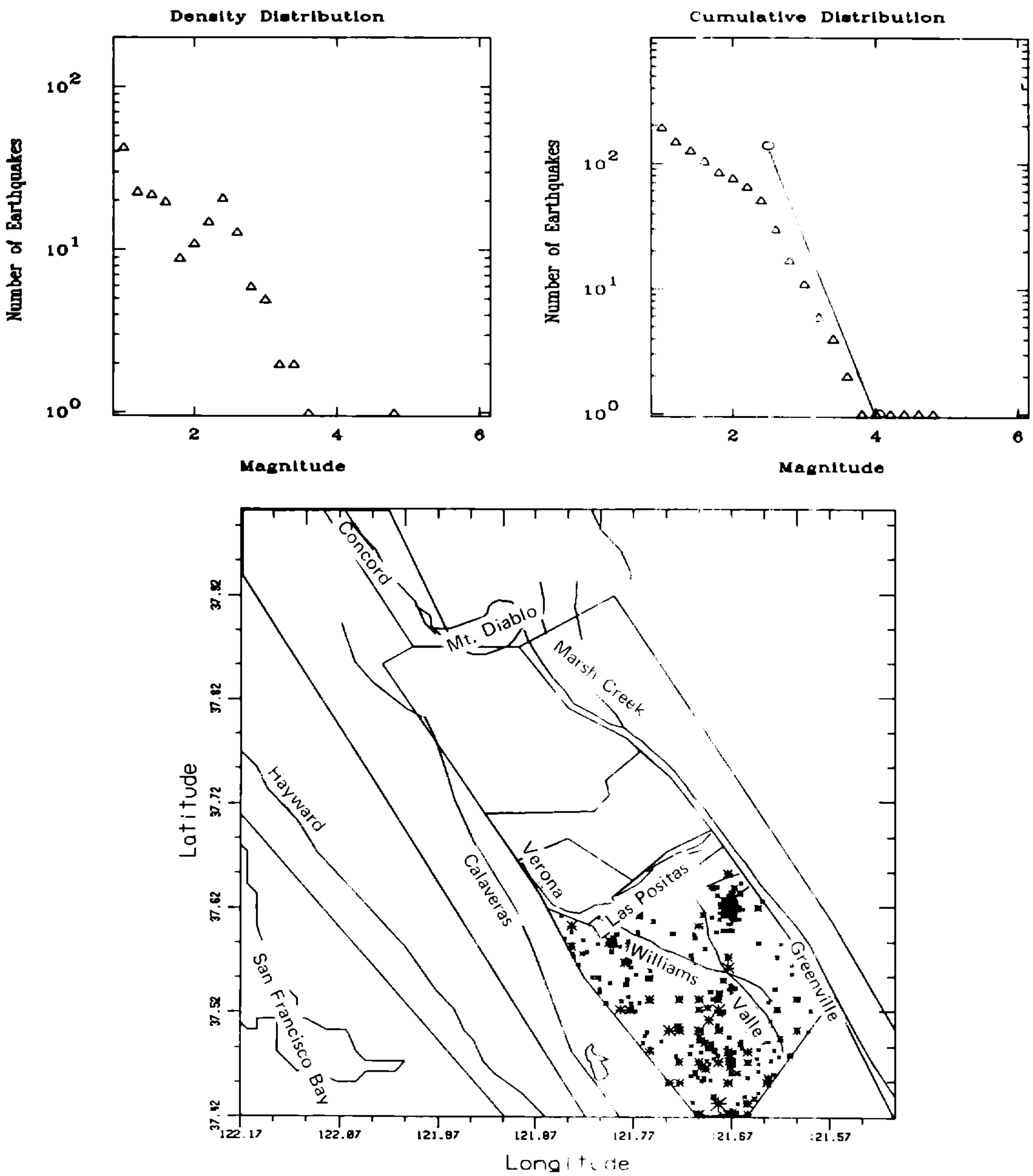


Figure A13. Hazard zone HZ3, Diablo Region, using the CDMG earthquake catalog. The b-value is 1.435 for $M_L \geq 2.50$

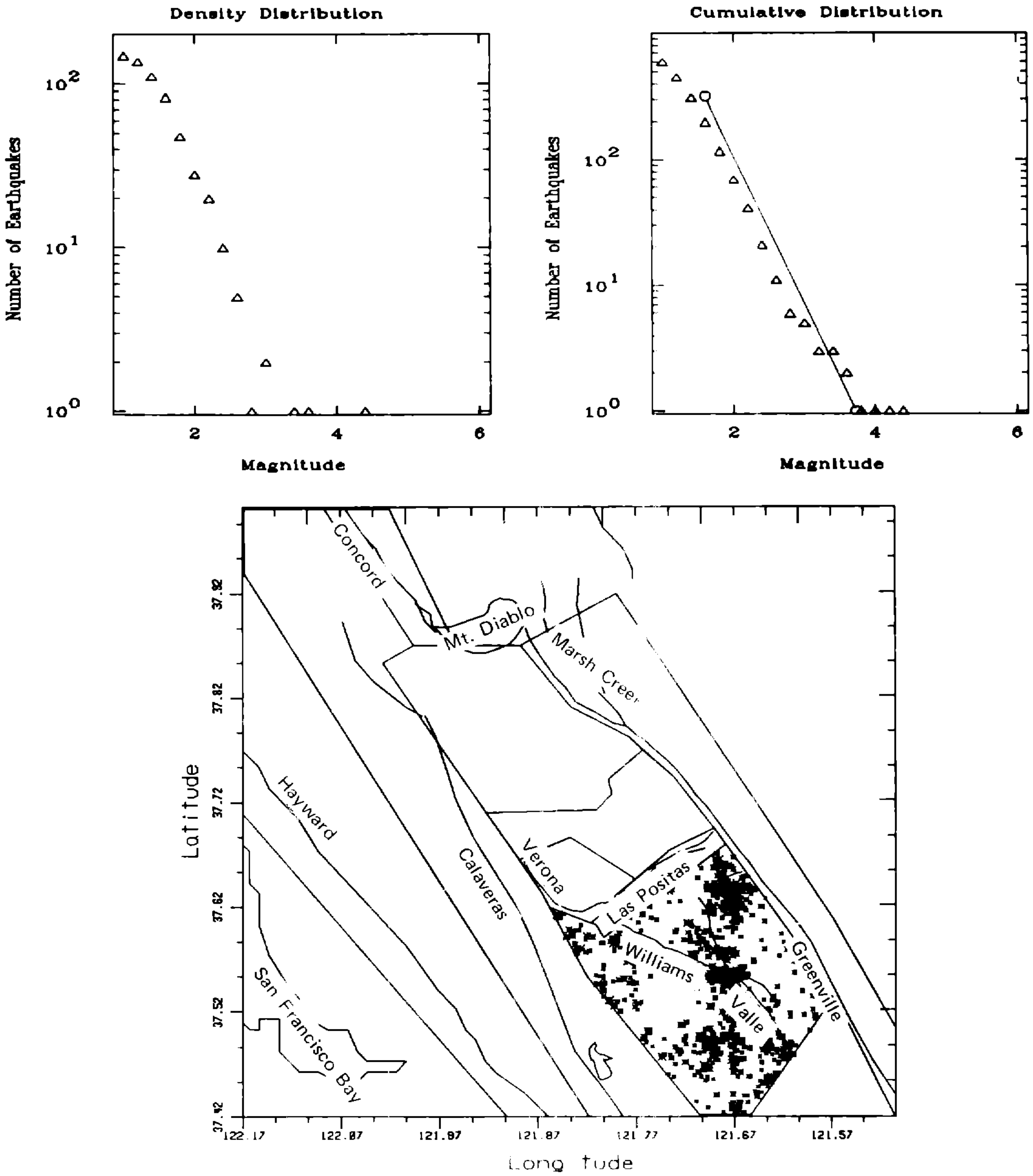


Figure A14. Hazard zone HZ3, Diablo Region, using the USGS earthquake catalog. The b-value is 1.174 for $M_L \geq 1.60$

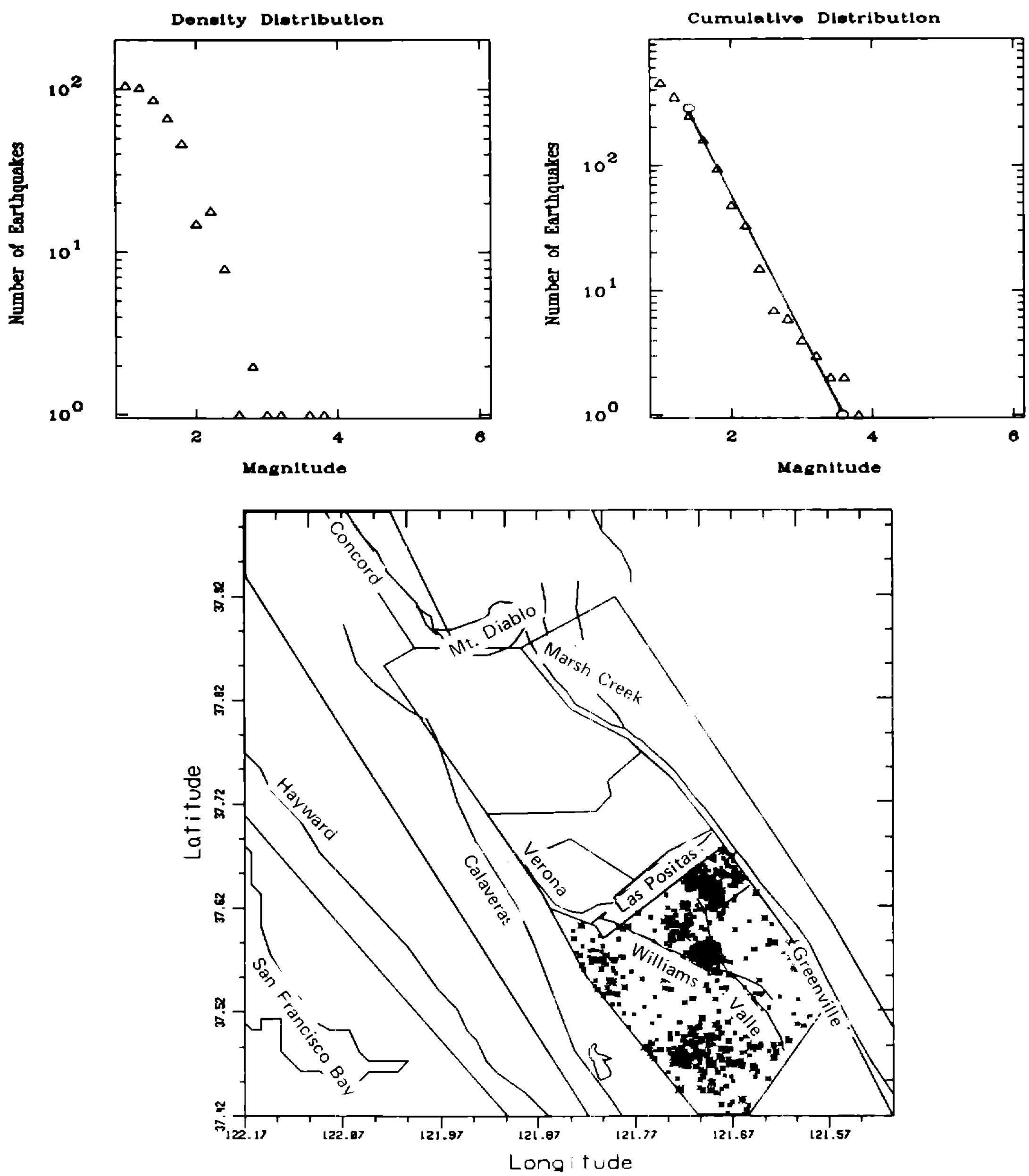


Figure A15. Hazard zone HZ3, Diablo Region, using the LLNL earthquake catalog. The b-value is 1.132 for $M_L \geq 1.40$

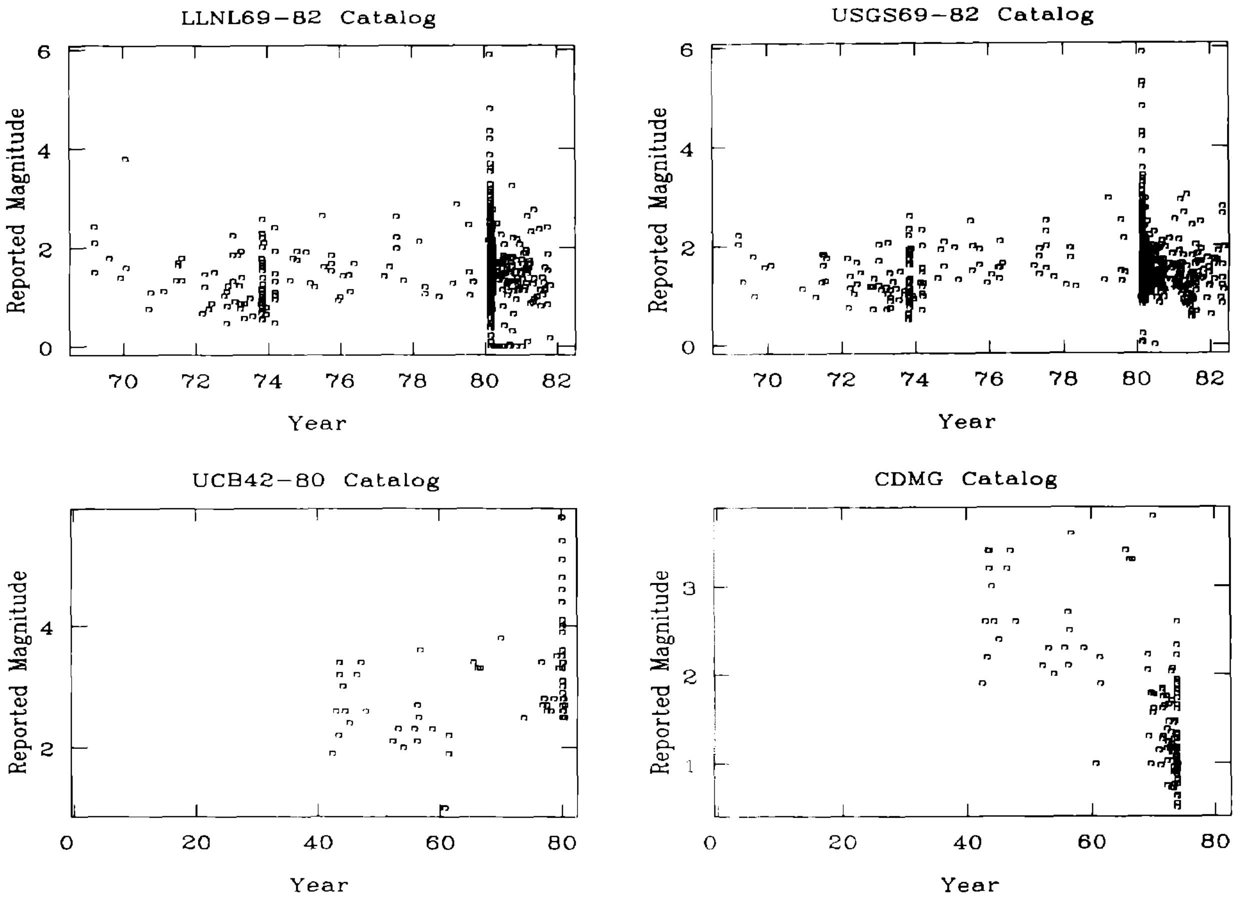


Figure A16. HZ4 - Greenville Fault - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

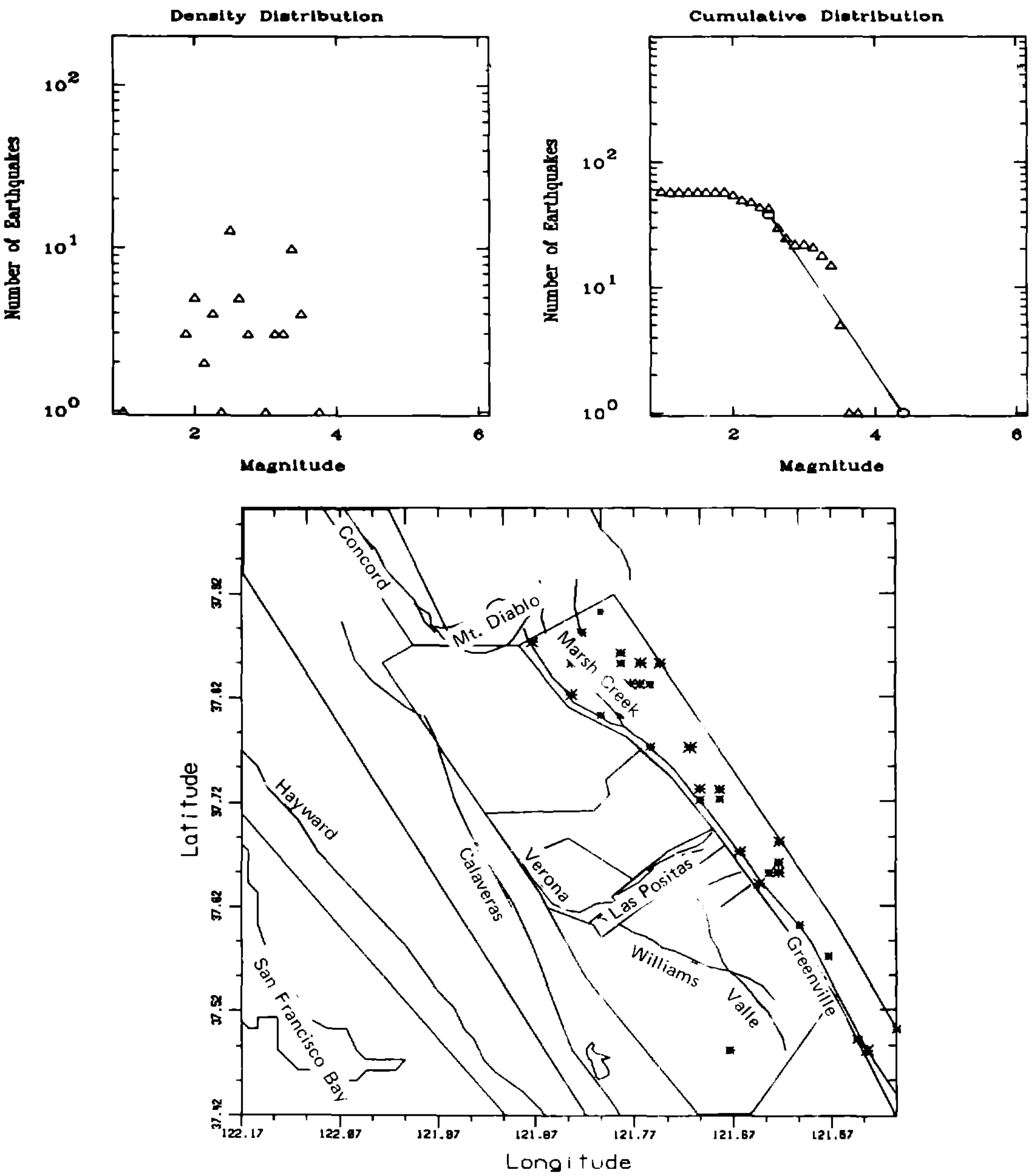


Figure A17. Hazard zone HZ4, Greenville Fault, using the UCB 1942-79 earthquake catalog. The b-value is 0.879 for $M_L \geq 2.50$

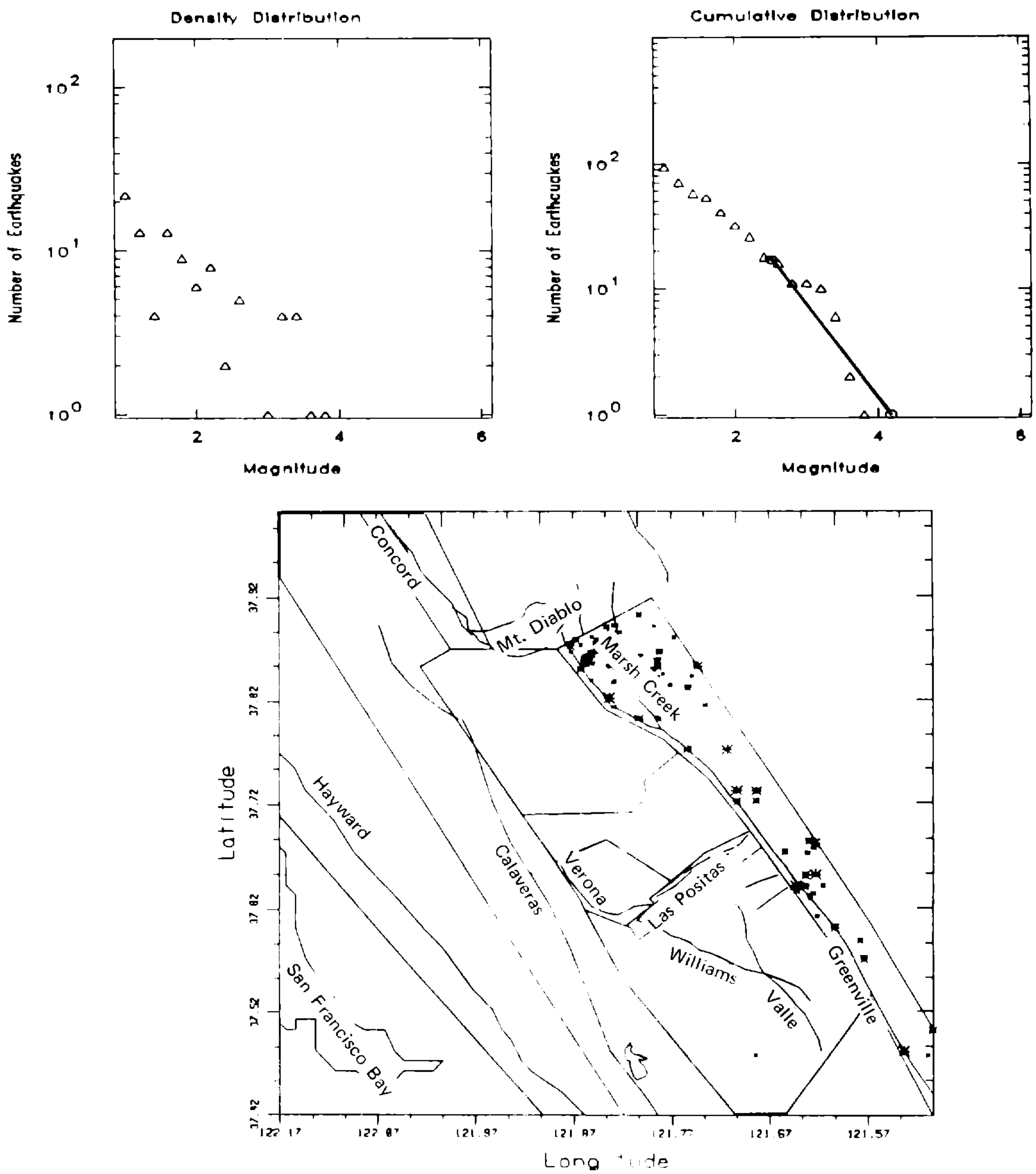


Figure A18. Hazard zone HZ4, Greenville Fault, using the CDMG earthquake catalog. The b-value is 0.937 for $M_L \geq 2.50$

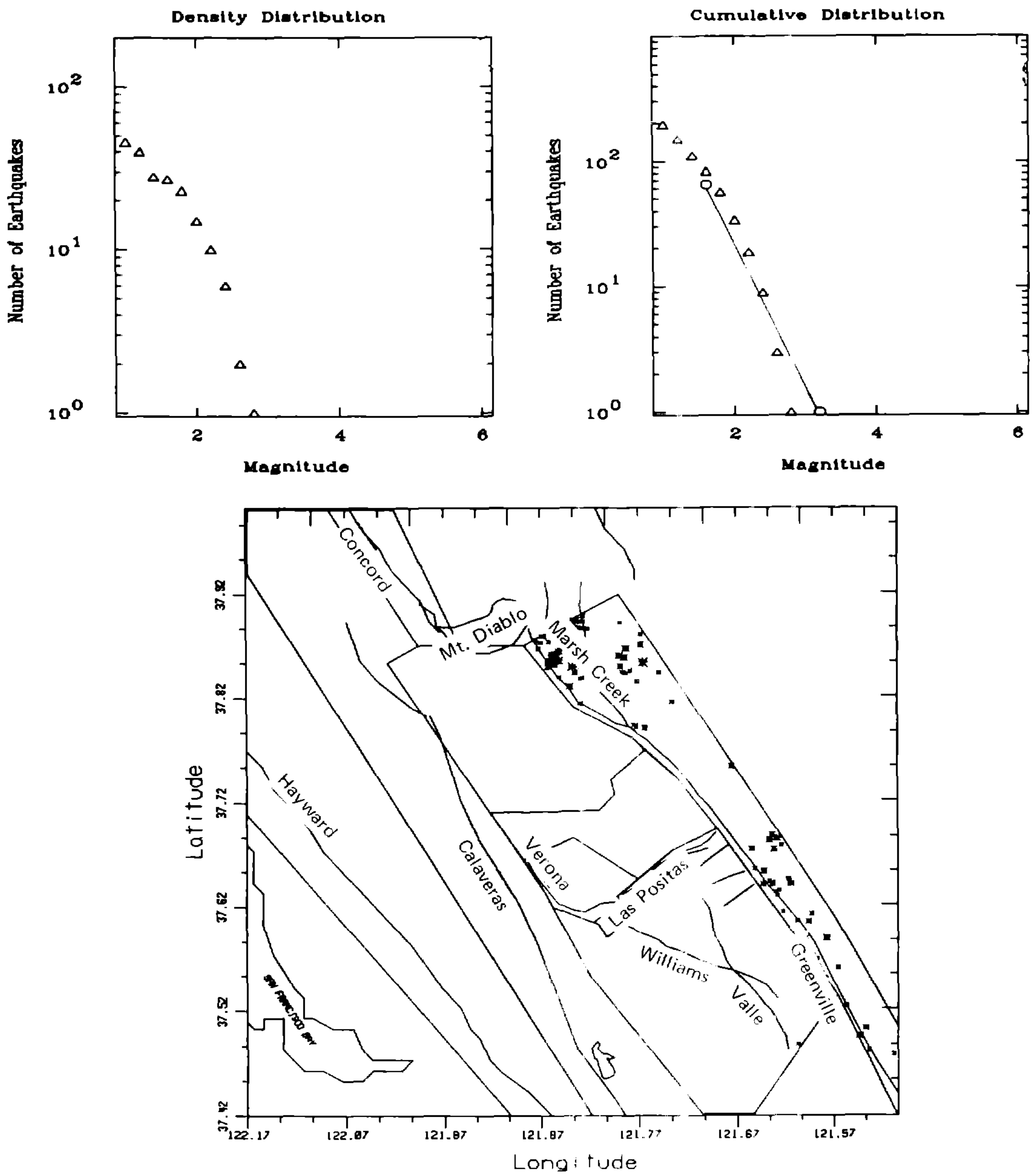


Figure A19. Hazard zone HZ4, Greenville Fault, using the USGS 1969-79 earthquake catalog. The b-value is 1.139 for $M_L \geq 1.60$

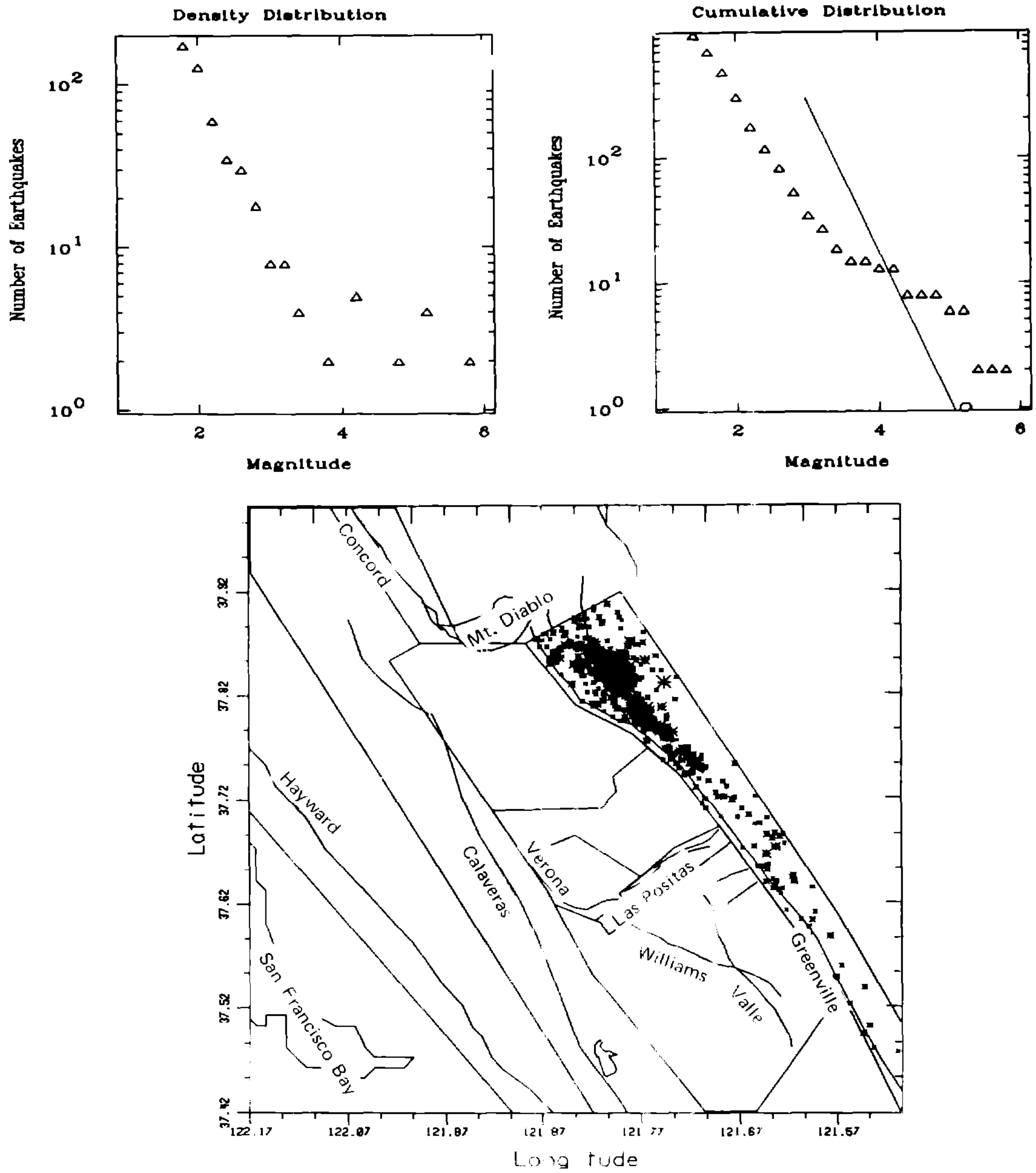


Figure A19a. Hazard zone HZ4, Greenville Fault, extending the catalog in Figure A19 to run from 1969-82 . The b-value is 0.910 for $M_L \geq 1.60$

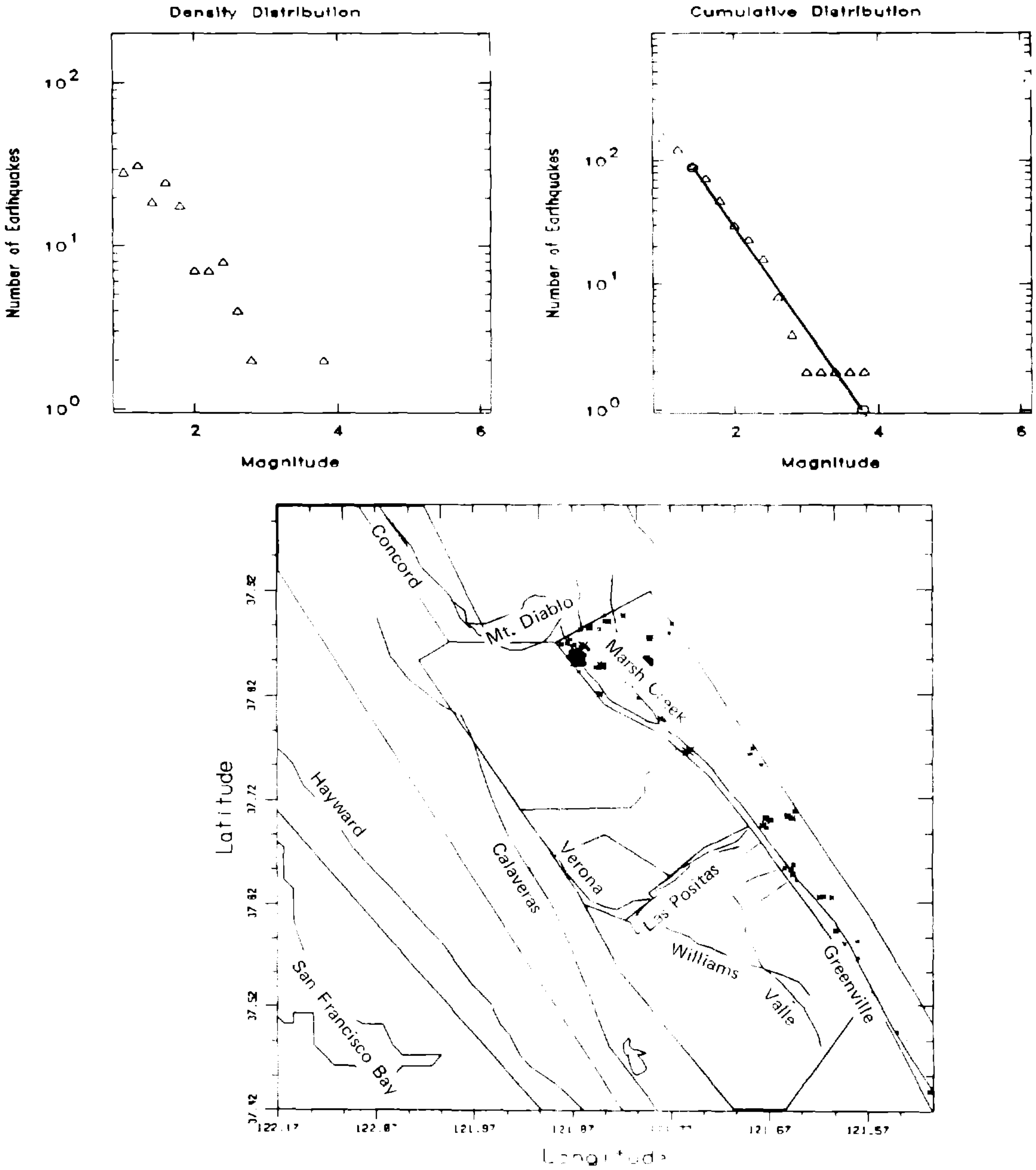


Figure A20. Hazard zone HZ4, Greenville Fault, using the LLNL 1969-79 earthquake catalog. The b-value is 0.875 for $M_L \geq 1.40$

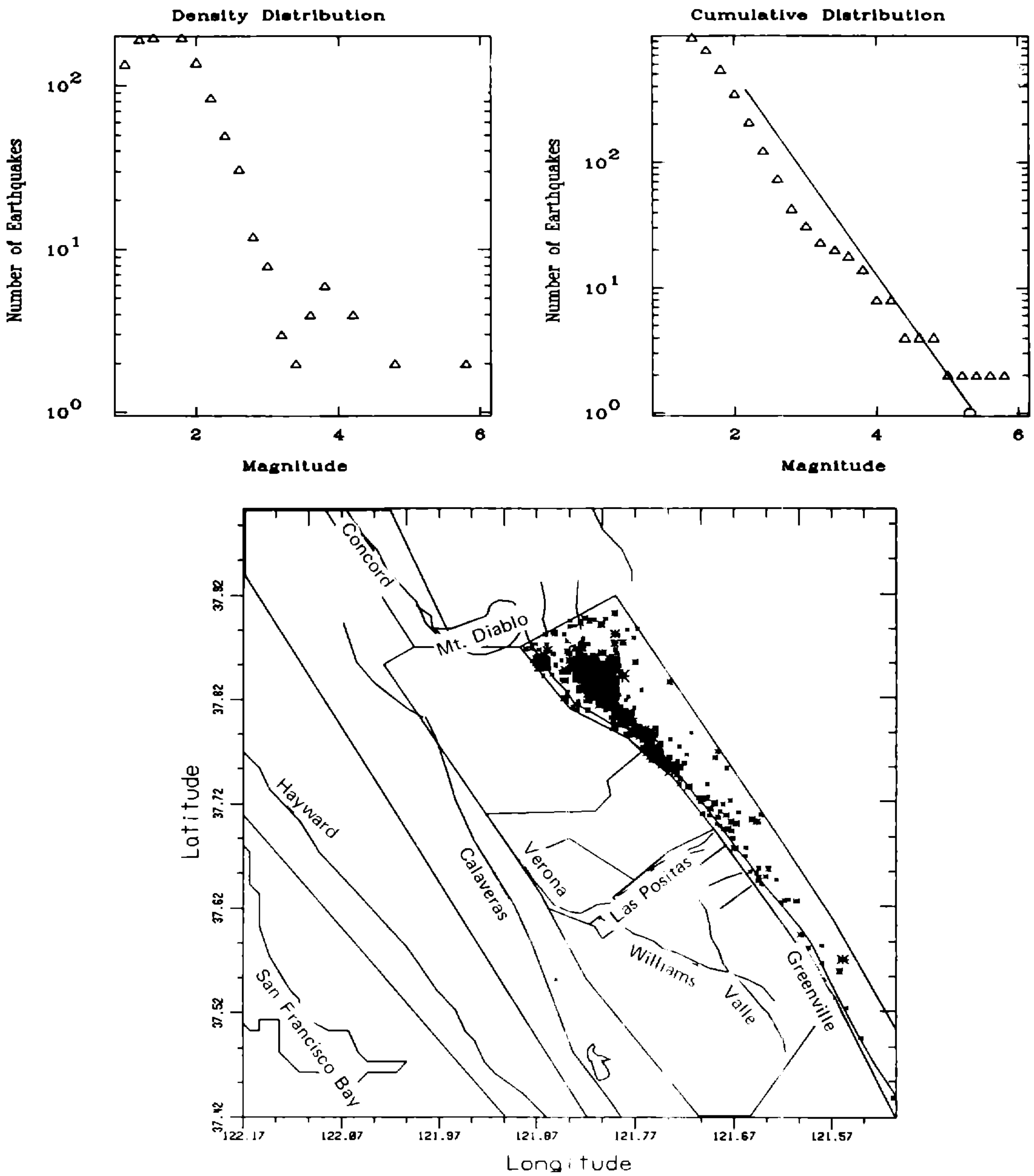


Figure A20a. Hazard zone HZ4, Greenville Fault, extending the catalog in Figure A20 to run from 1969-82. The b-value is 0.754 for $M_L \geq 1.40$

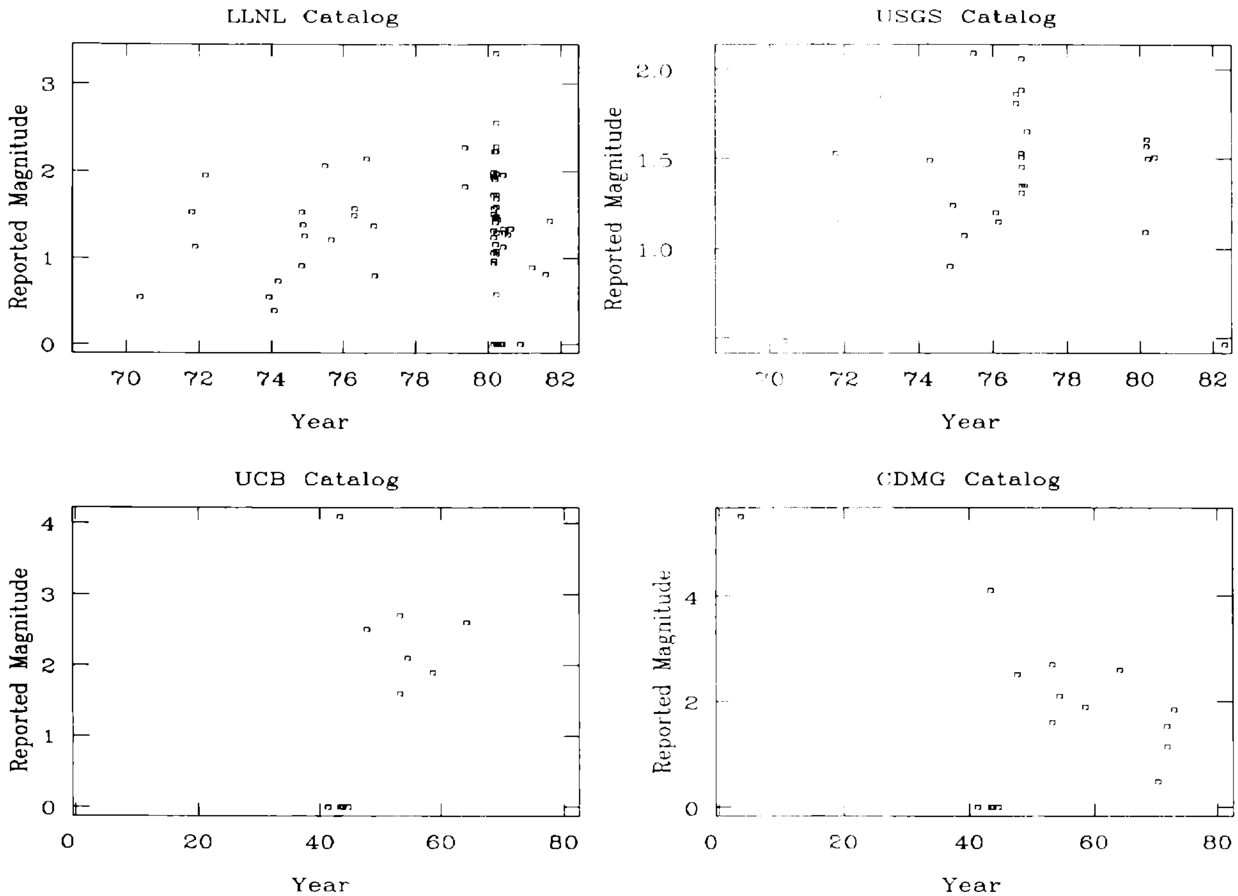


Figure A21. HZ5 - Las Positas Fault - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

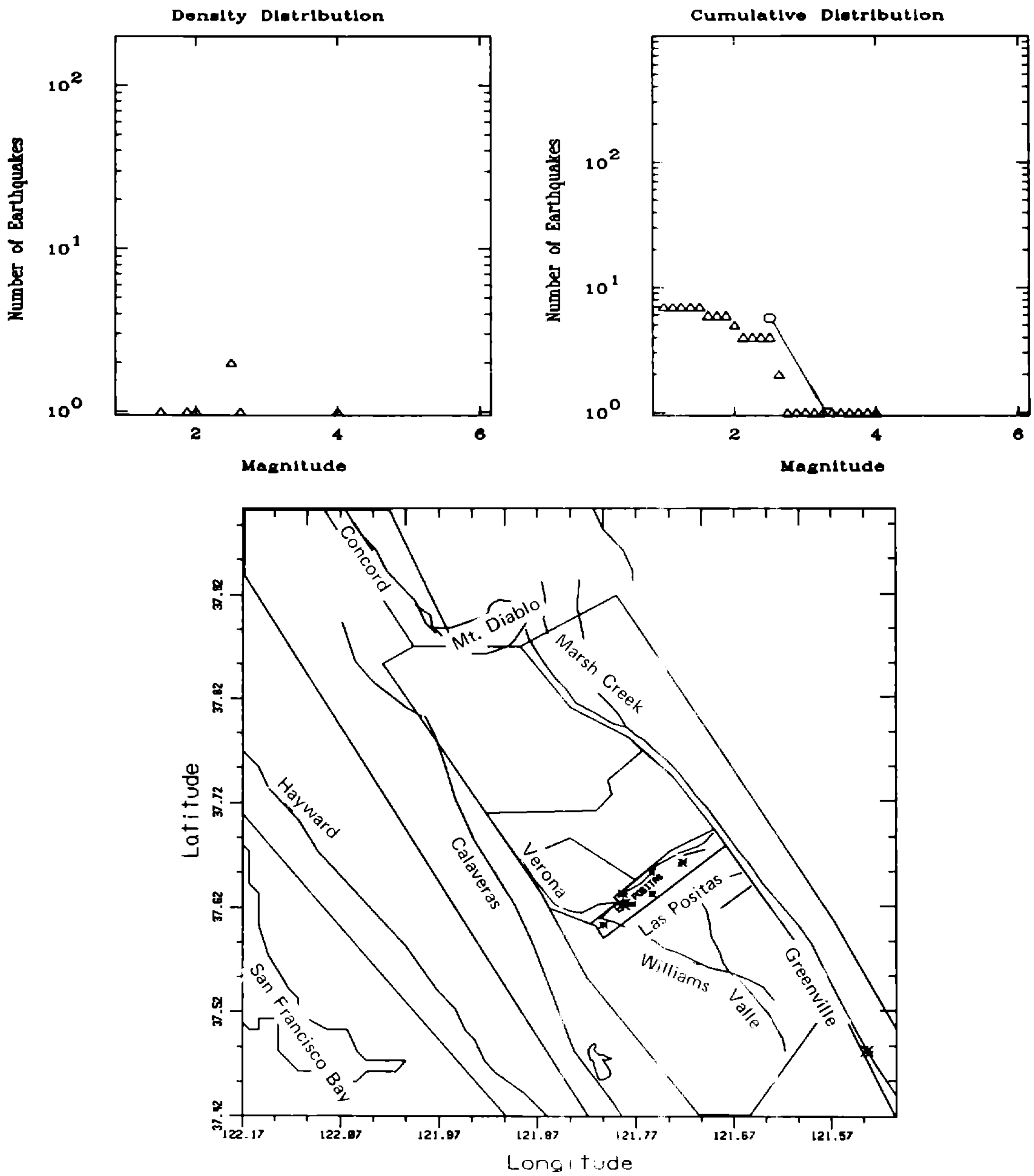


Figure A22. Hazard zone HZ5, Las Positas Fault, using the UCB earthquake catalog. The b-value is 0.914 for $M_L \geq 2.50$

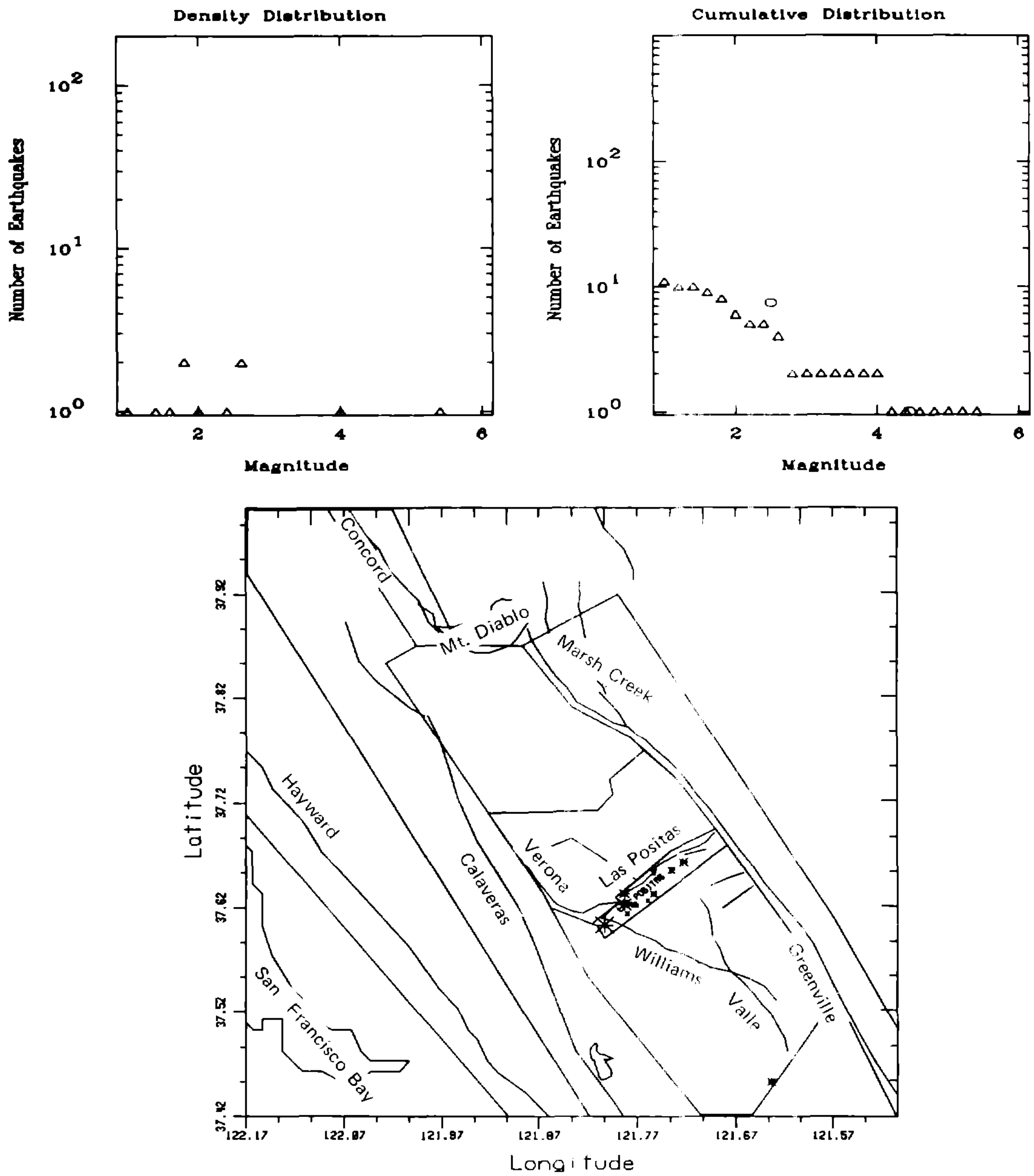


Figure A23. Hazard zone HZ5, Las Positas Fault, using the CDMG earthquake catalog. The b-value is UNDEFINED for $M_L \geq 2.50$

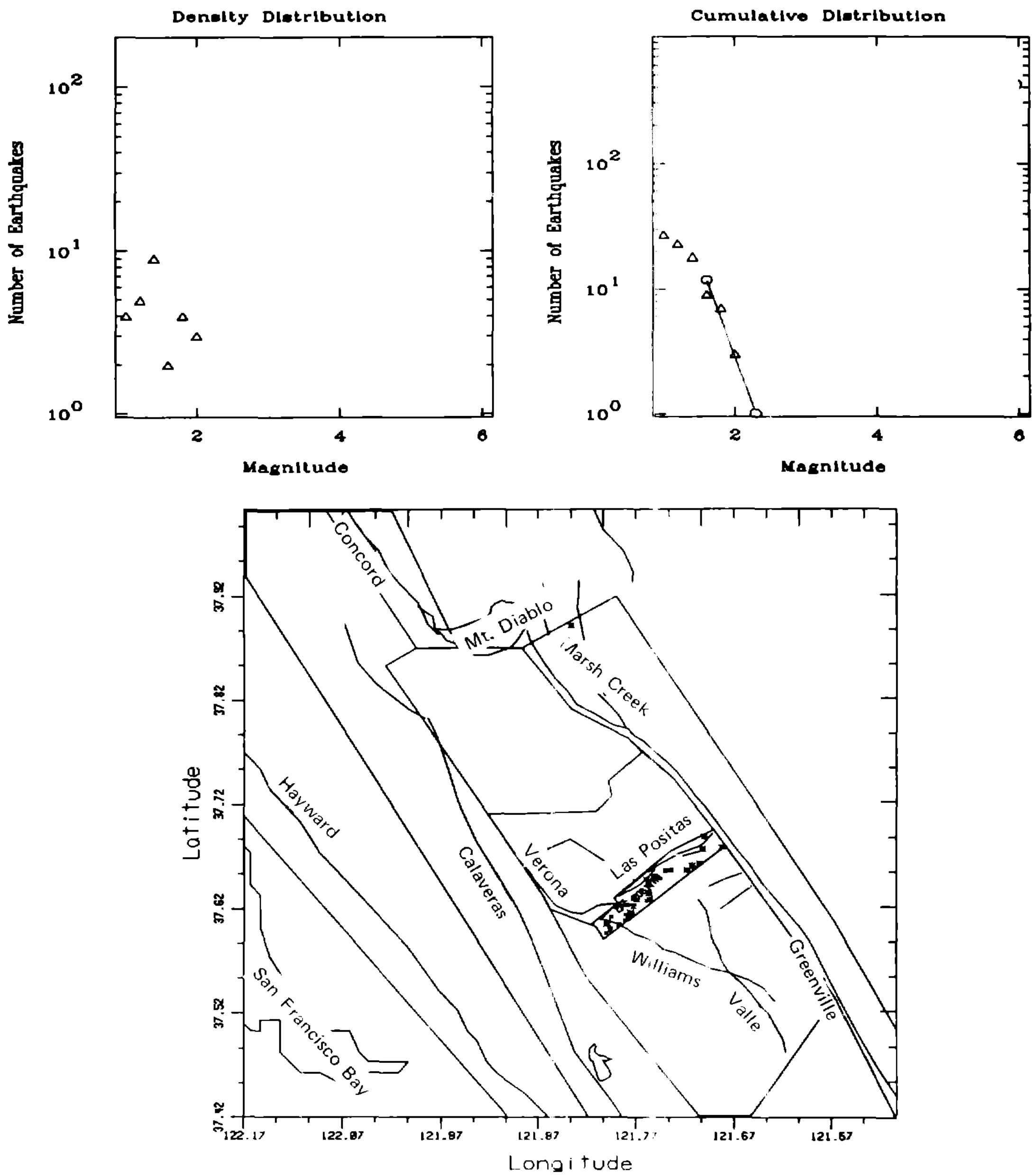


Figure A24. Hazard zone HZ5, Las Positas Fault, using the USGS earthquake catalog. The b-value is 1.563 for $M_L \geq 1.60$

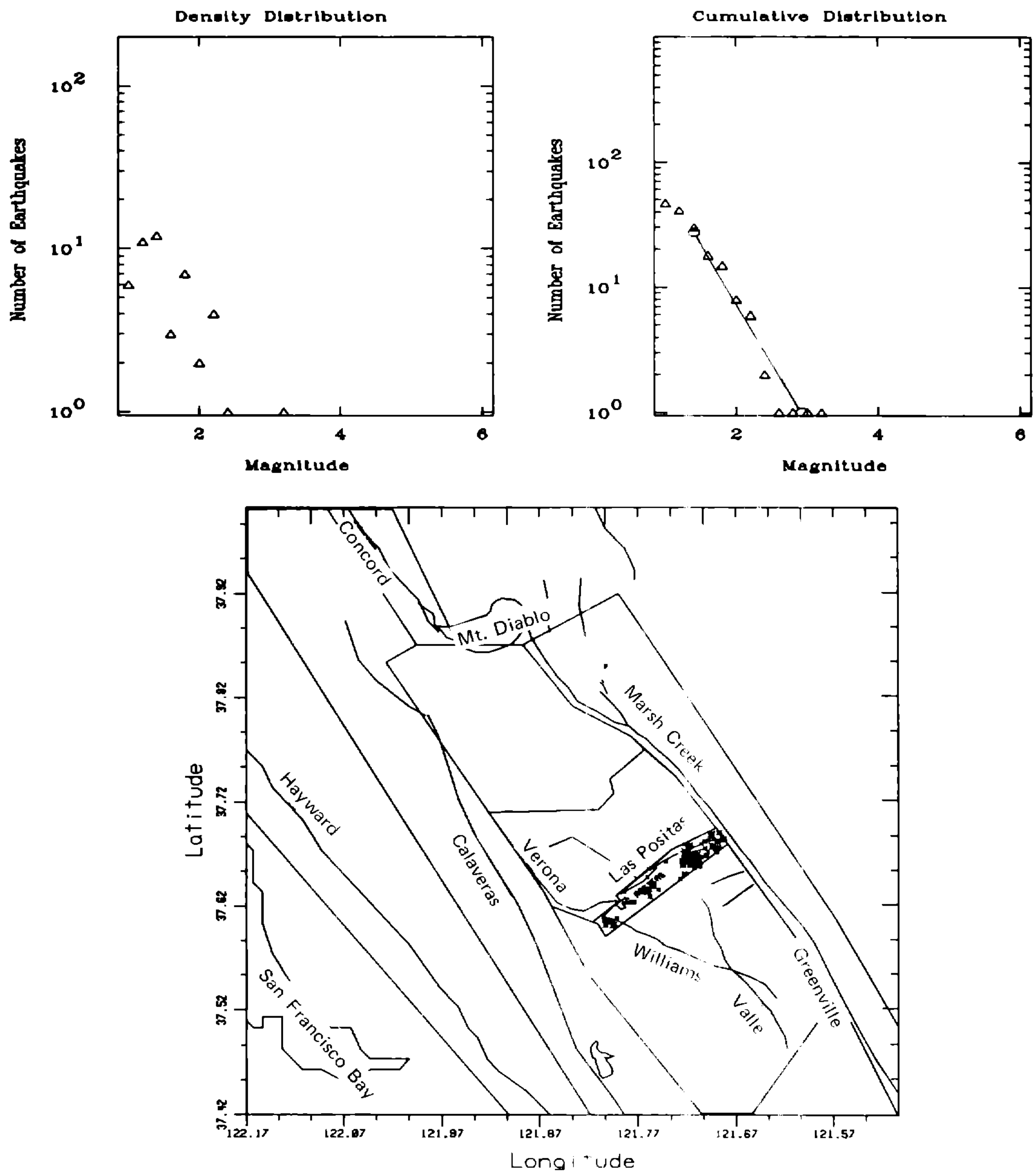


Figure A25. Hazard zone HZ5, Las Positas Fault, using the LLNL earthquake catalog. The b-value is 0.941 for $M_L \geq 1.40$

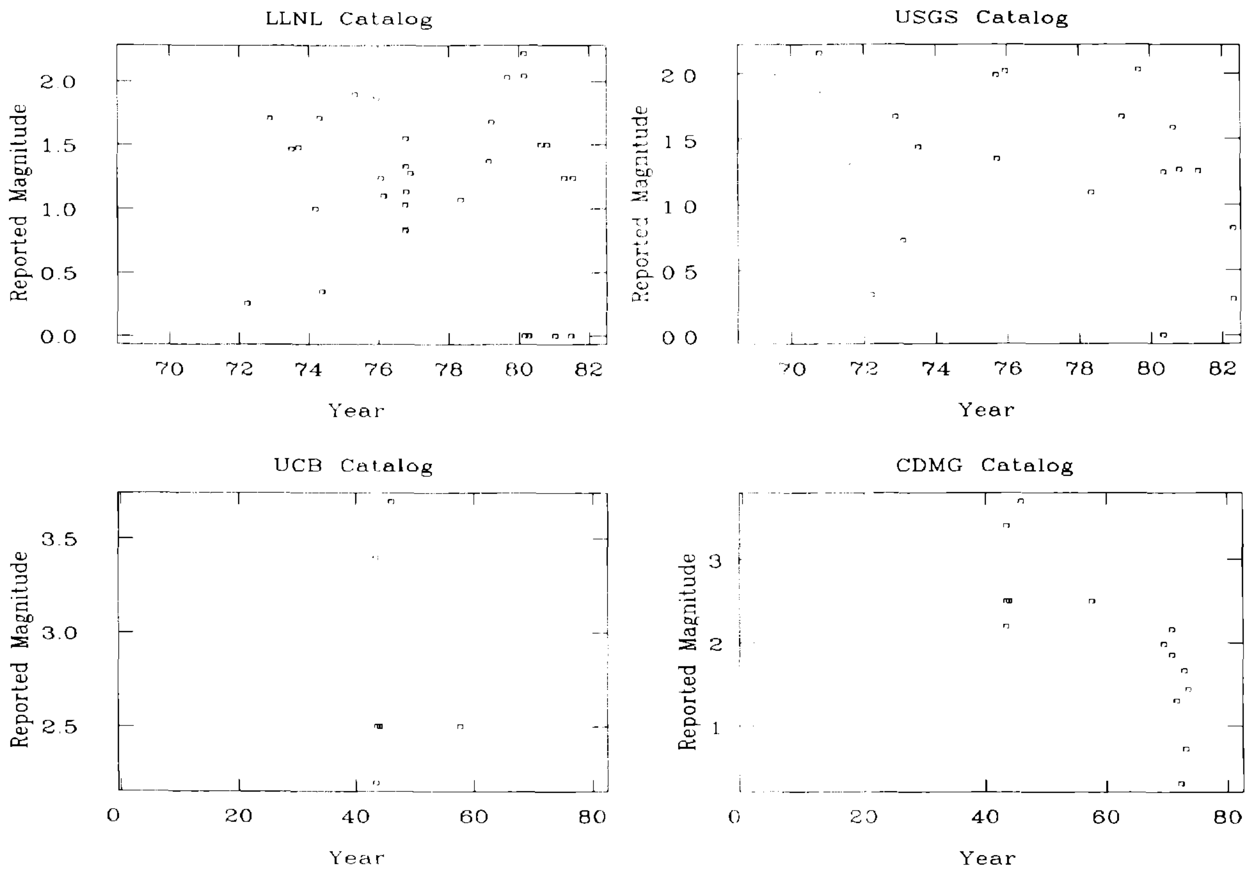


Figure A26. HZ6 - Verona Fault - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

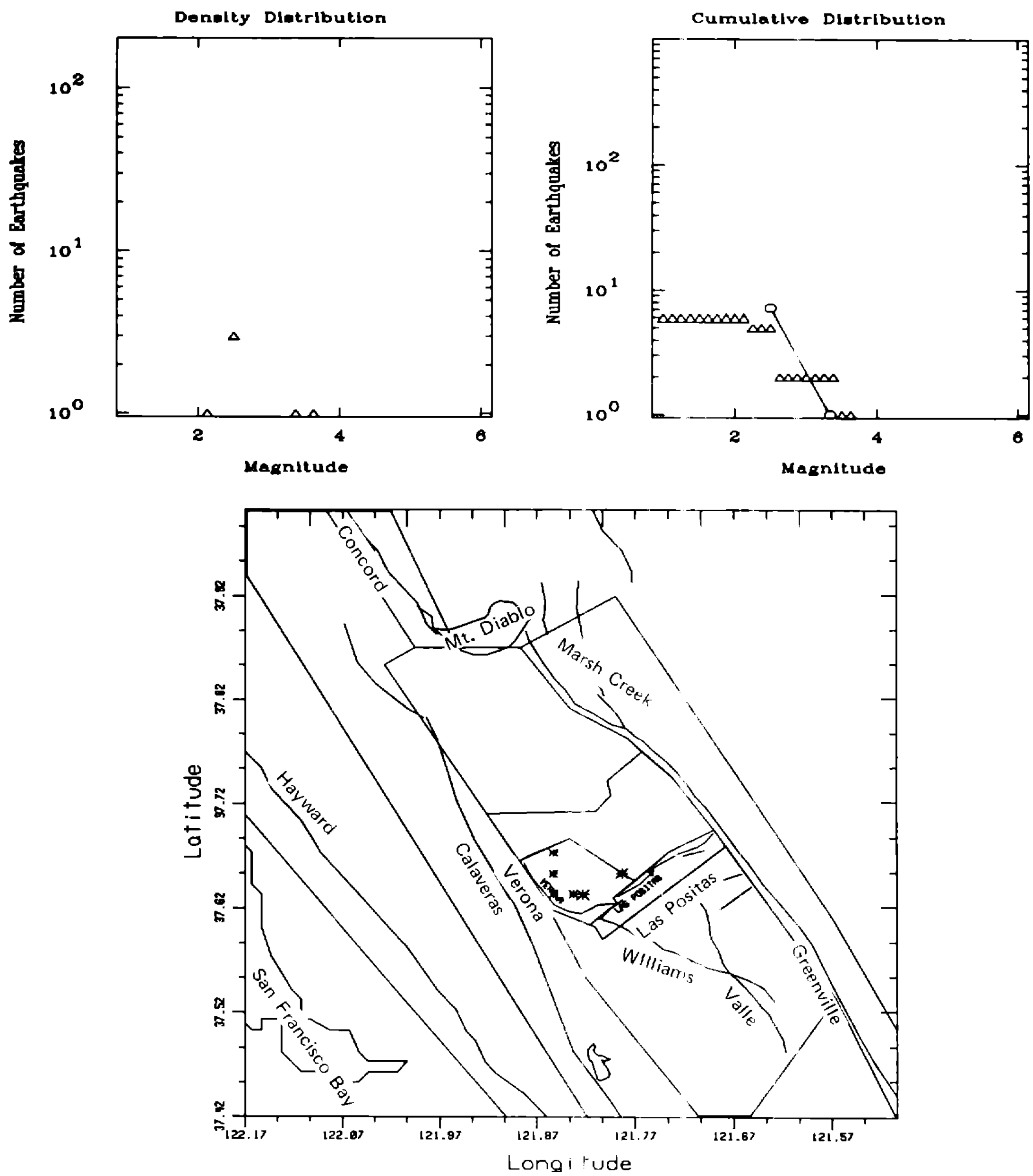


Figure A27. Hazard zone HZ6, Verona Fault, using the UCB earthquake catalog. The b-value is UNDEFINED for $M_L \geq 2.50$

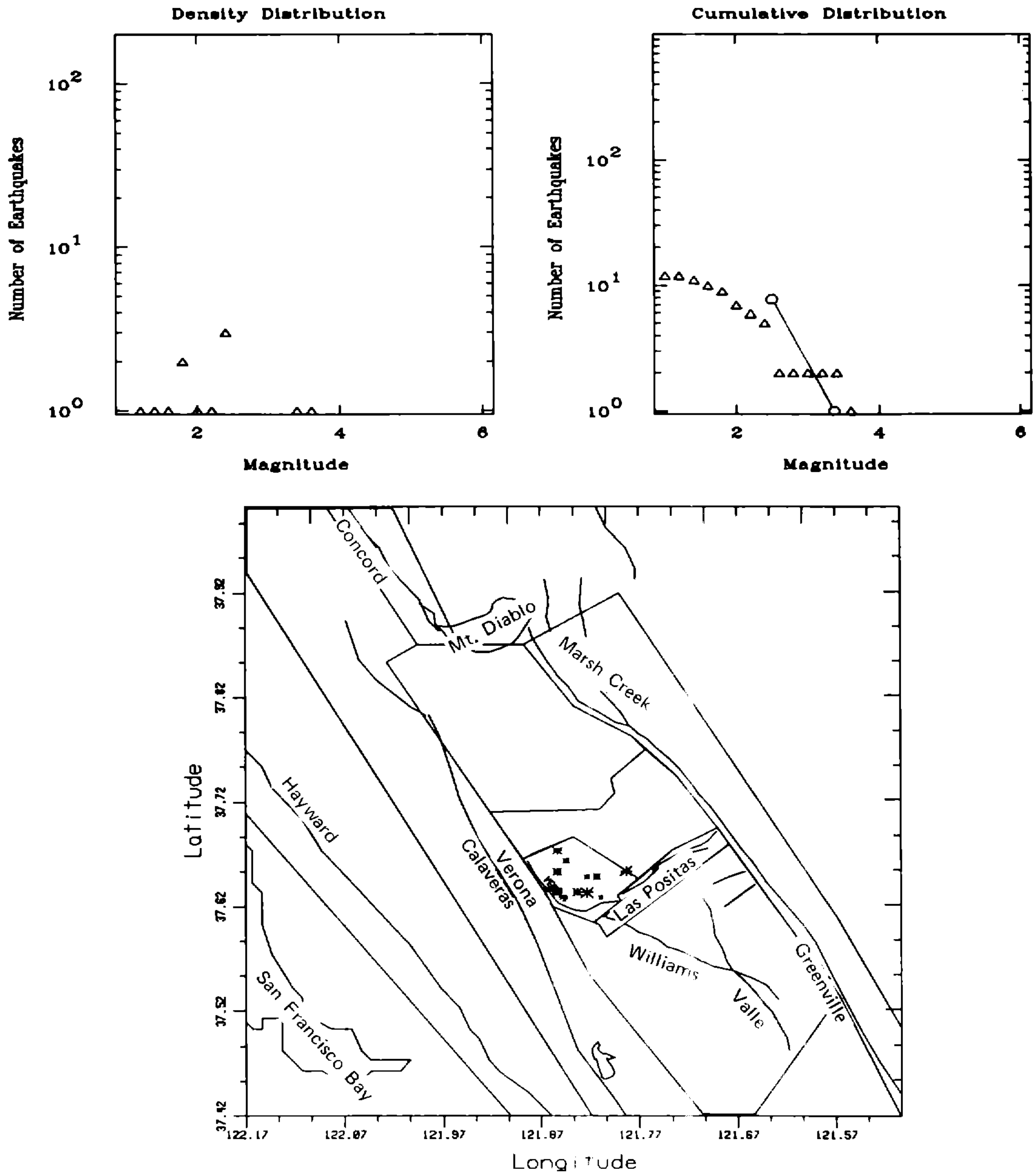
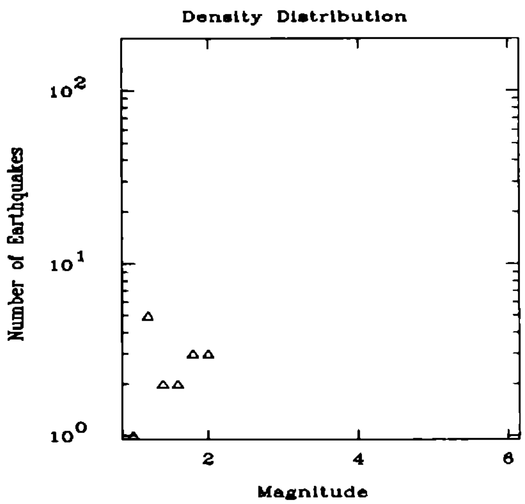
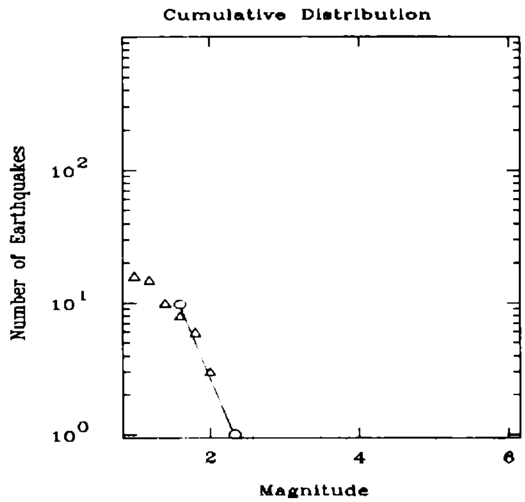


Figure A28. Hazard zone HZ6, Verona Fault, using the CDMG earthquake catalog. The b-value is UNDEFINED for $M_L \geq 2.50$





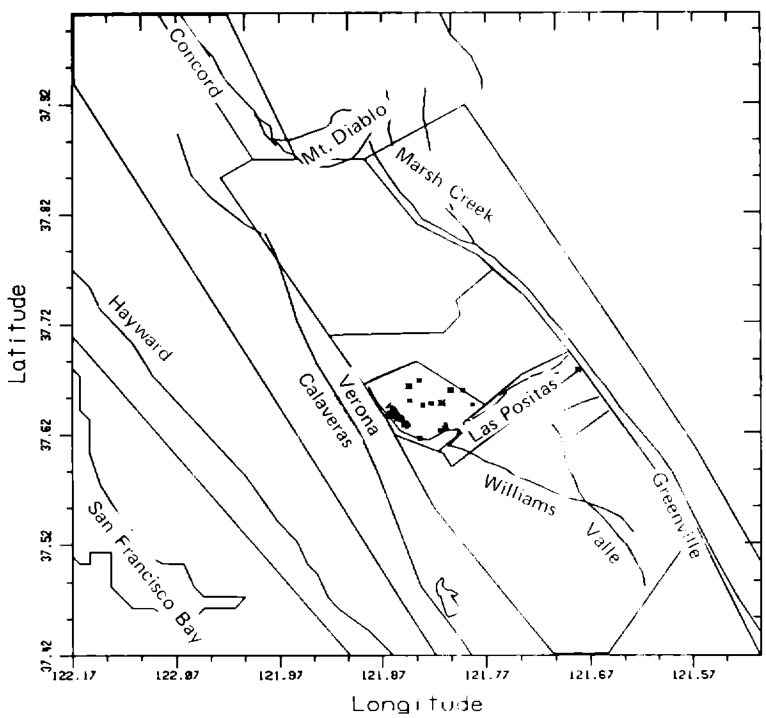


Figure A29. Hazard zone HZ6, Verona Fault, using the USGS earthquake catalog. The b-value is UNDEFINED for $M_L \geq 1.60$

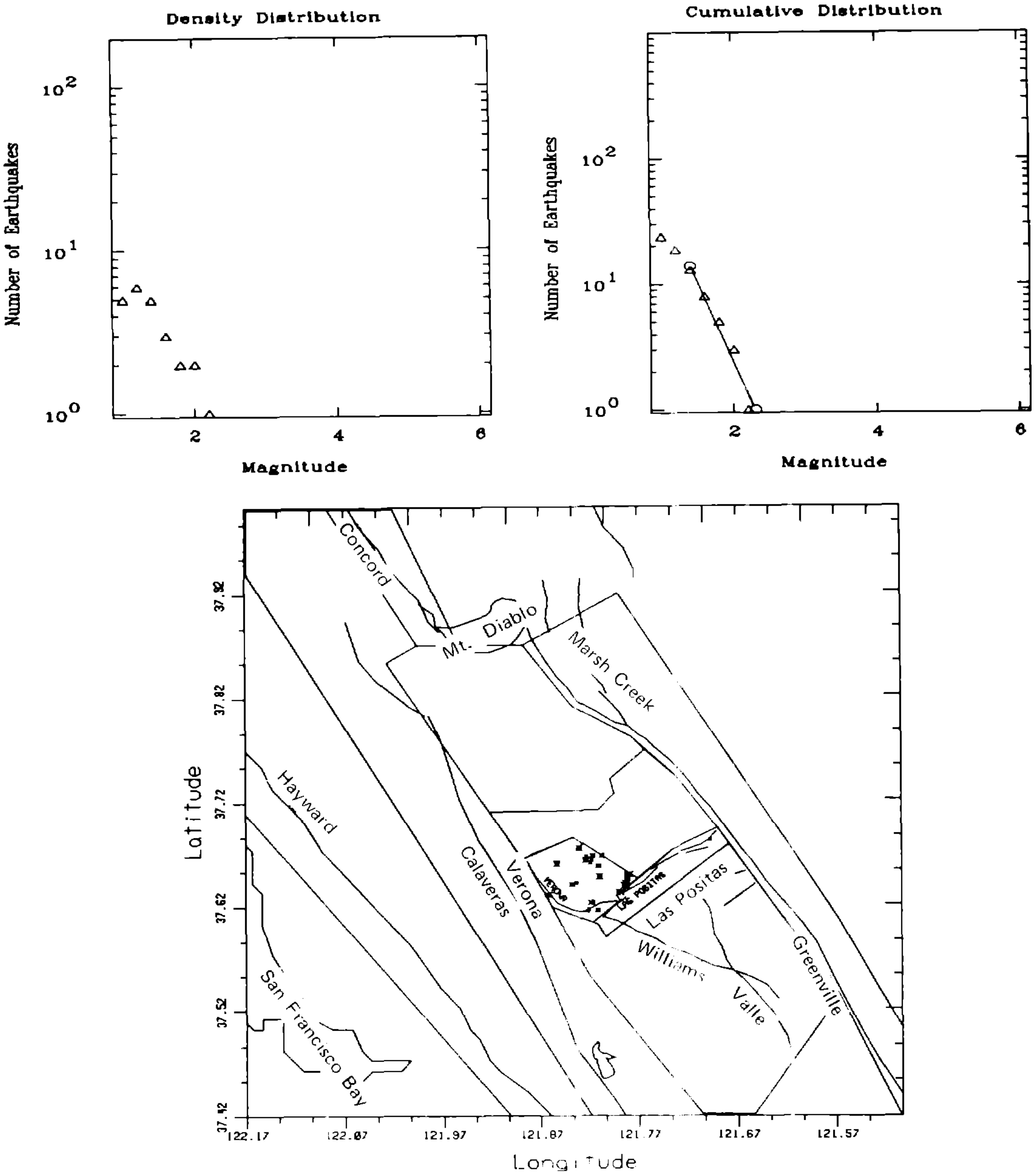


Figure A30. Hazard zone HZ6, Verona Fault, using the LLNL earthquake catalog. The b-value is 1.266 for $M_L \geq 1.40$

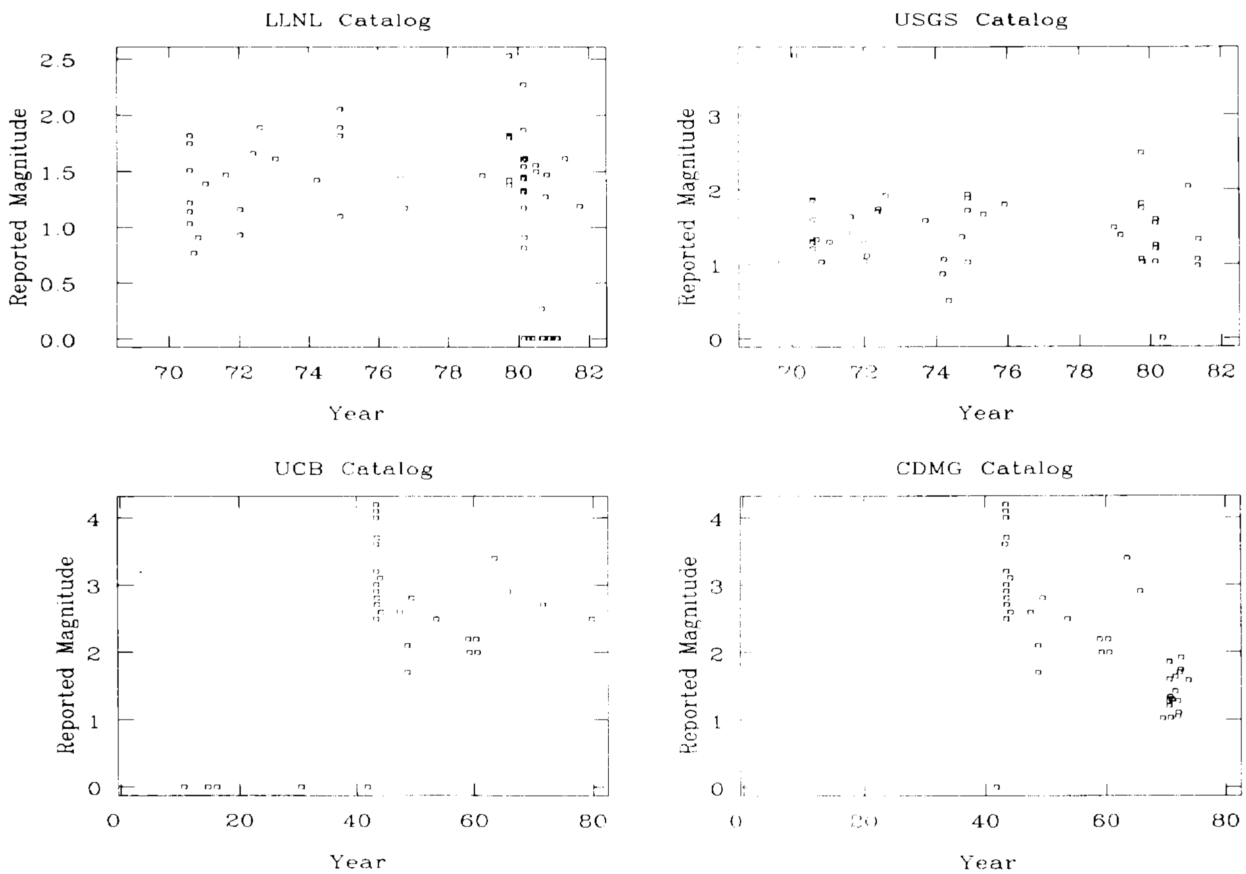


Figure A31. HZ7 - Livermore Valley Region - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

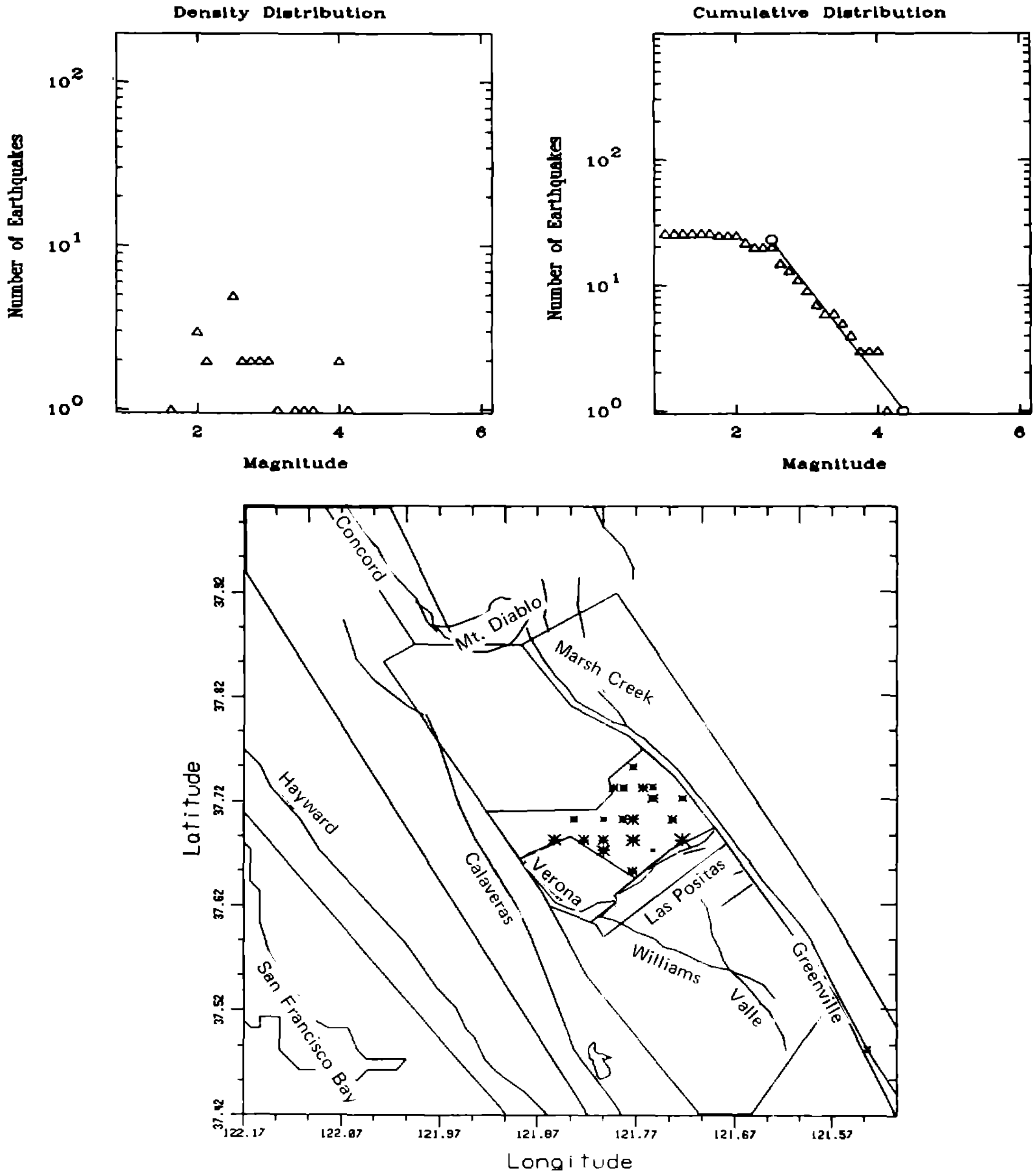


Figure A32. Hazard zone HZ7, Livermore Valley Region, using the UCB earthquake catalog. The b-value is 0.736 for $M_L \geq 2.50$

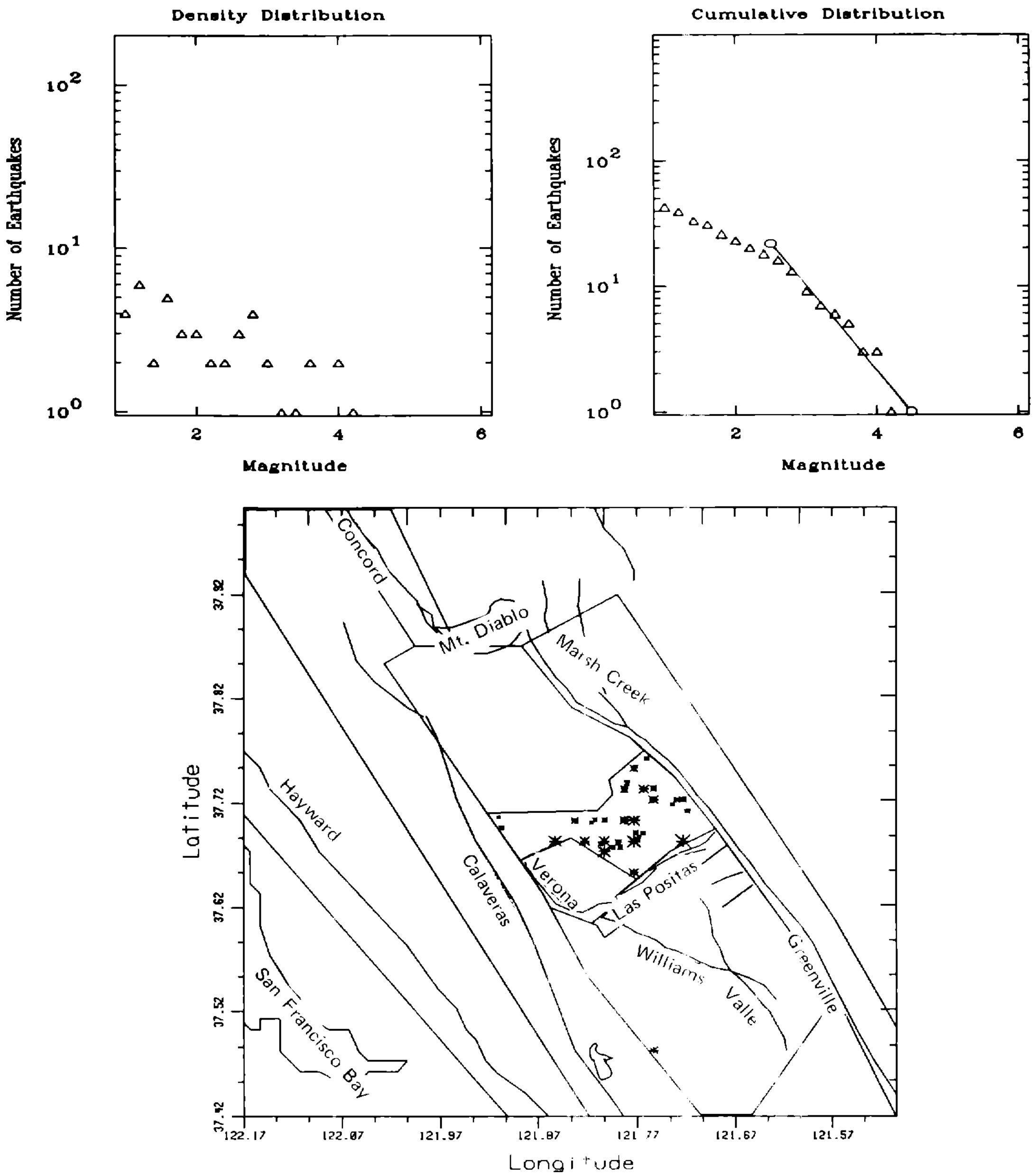


Figure A33. Hazard zone HZ7, Livermore Valley Region, using the CDMG earthquake catalog. The b-value is 0.675 for $M_L \geq 2.50$

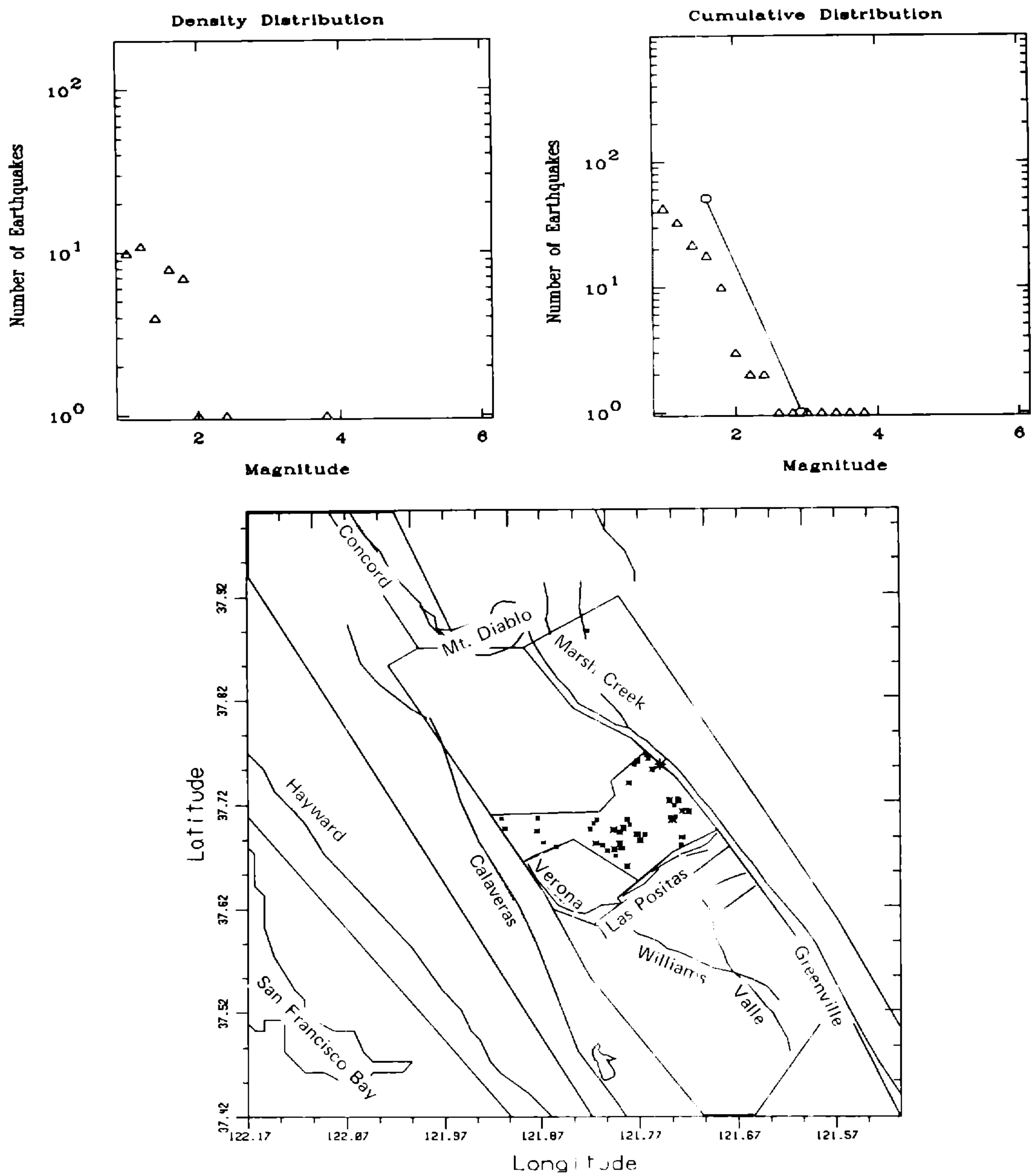


Figure A34. Hazard zone HZ7, Livermore Valley Region, using the USGS earthquake catalog. The b-value is 1.301 for $M_L \geq 1.60$

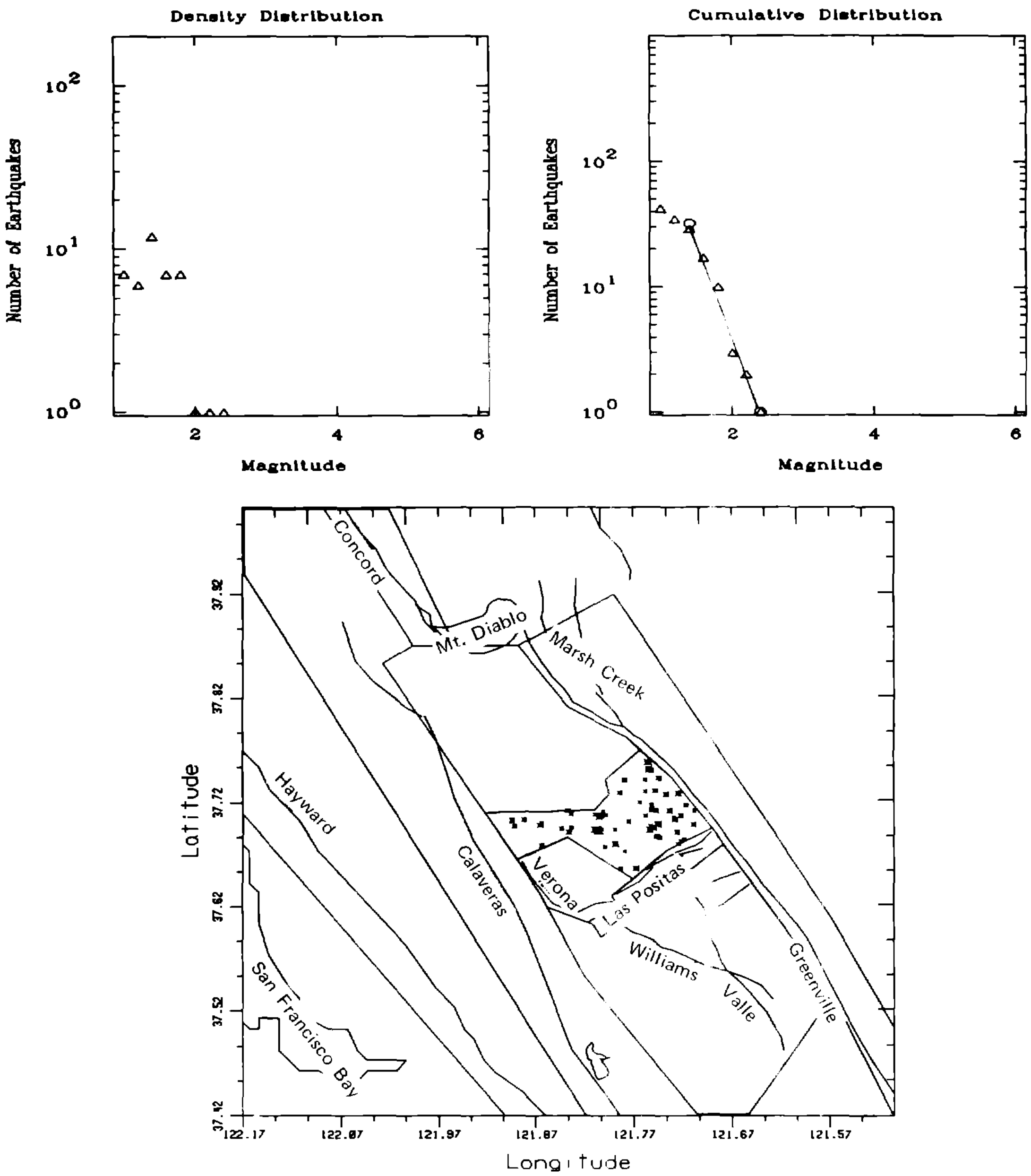


Figure A35. Hazard zone HZ7, Livermore Valley Region, using the LLNL earthquake catalog. The b-value is 1.521 for $M_L \geq 1.40$

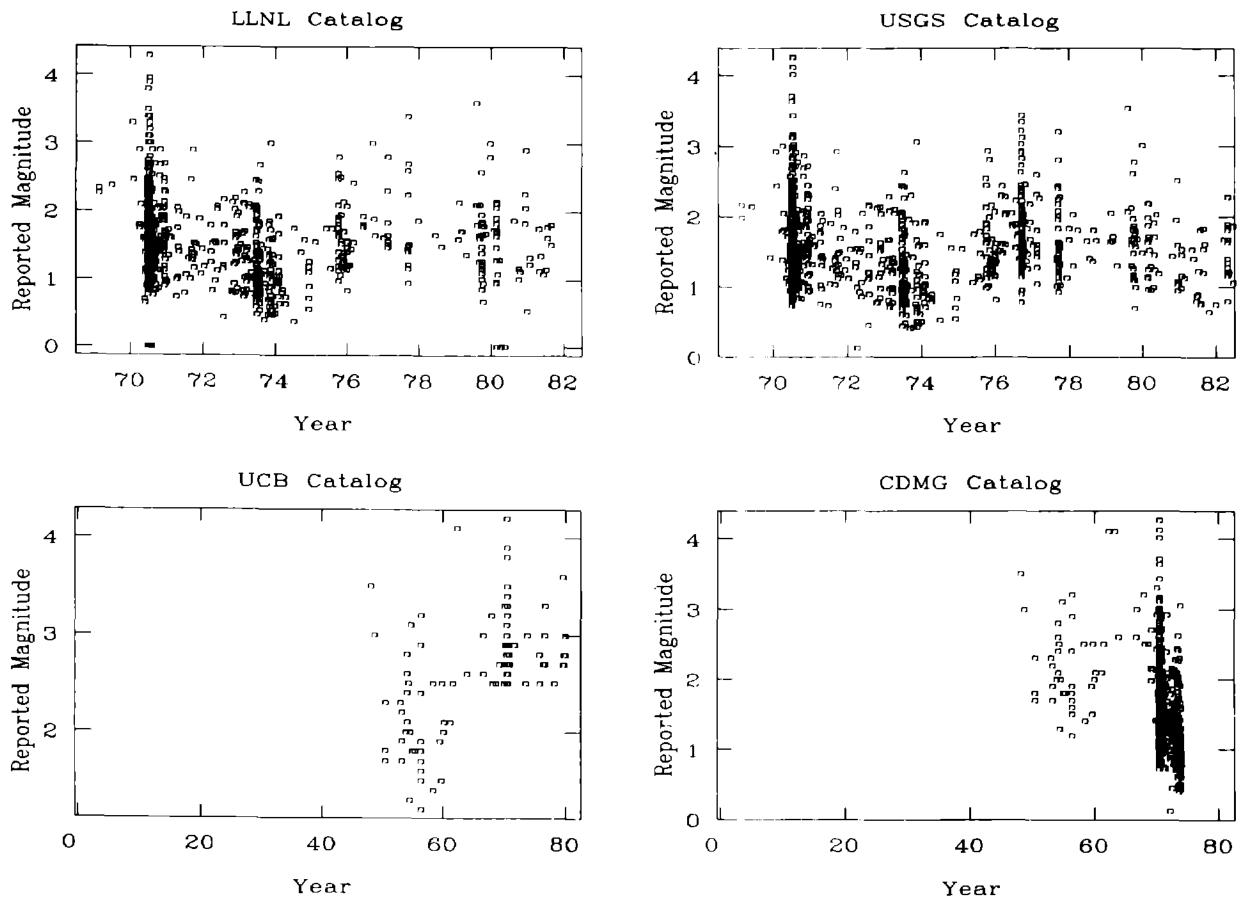


Figure A36. HZ8 - Danville Region - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

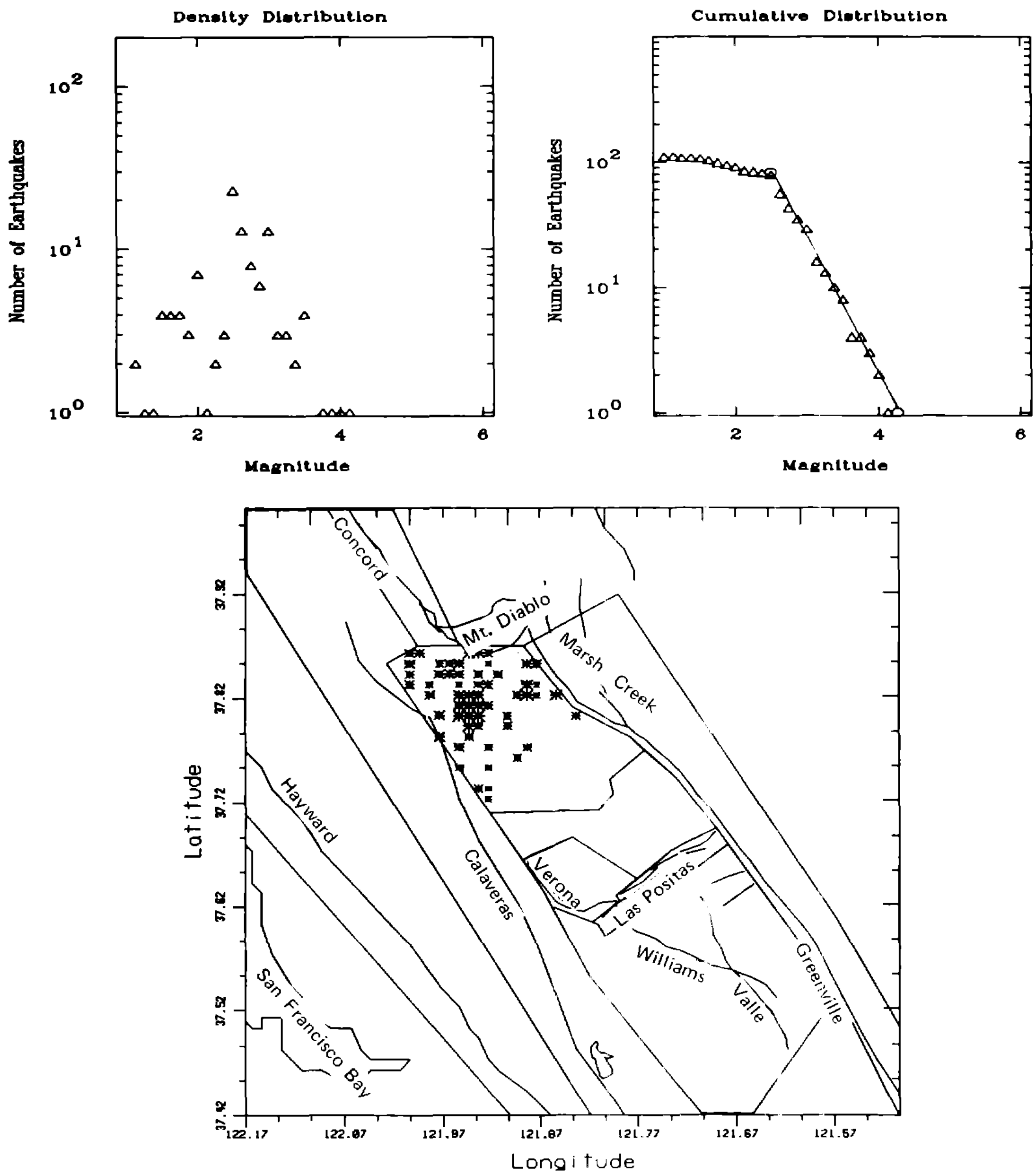


Figure A37. Hazard zone HZ8, Danville Region, using the UCB earthquake catalog. The b-value is 1.086 for $M_L \geq 2.50$

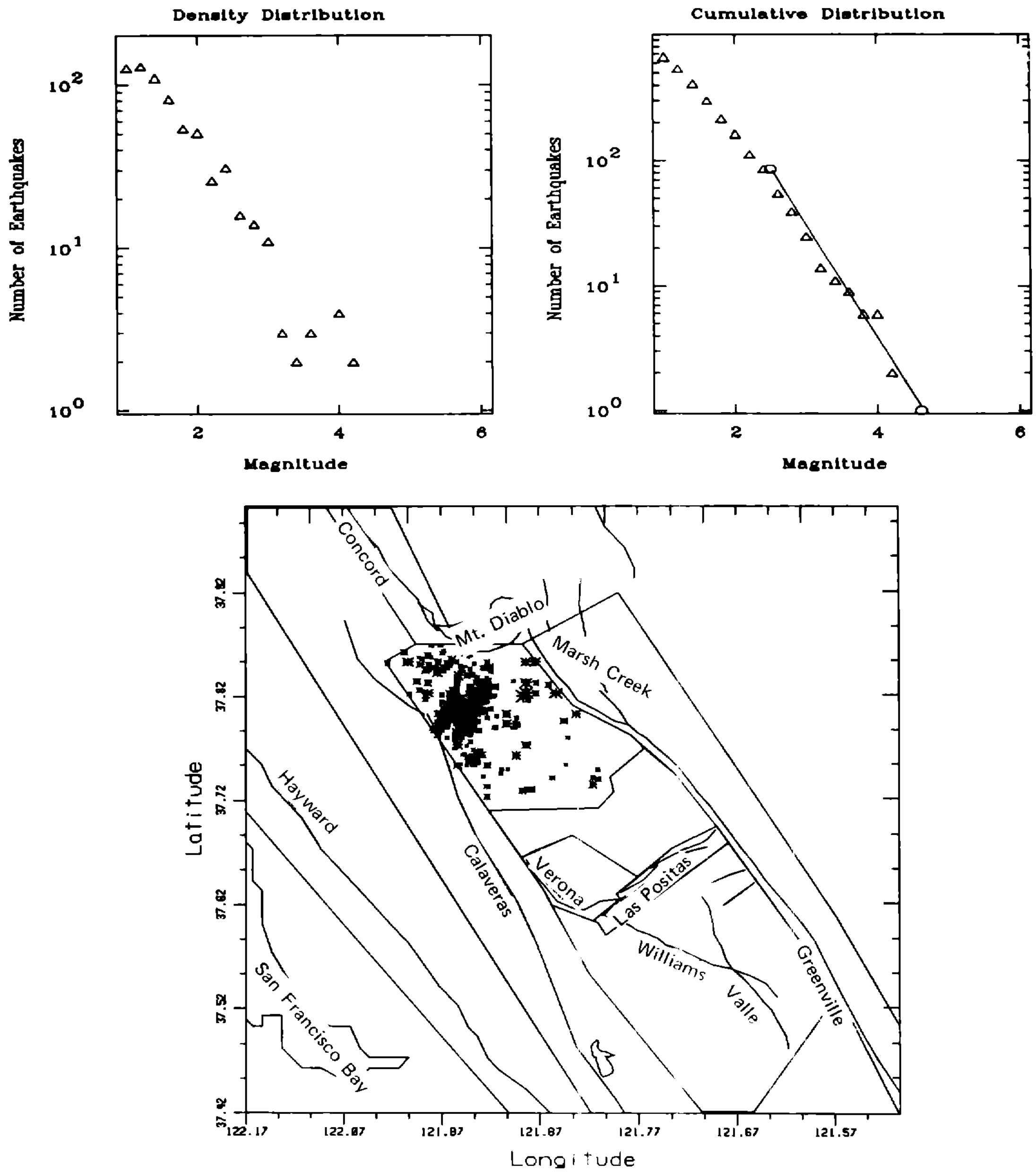


Figure A38. Hazard zone HZ8, Danville Region, using the CDMG earthquake catalog. The b-value is 0.874 for $M_L \geq 2.50$

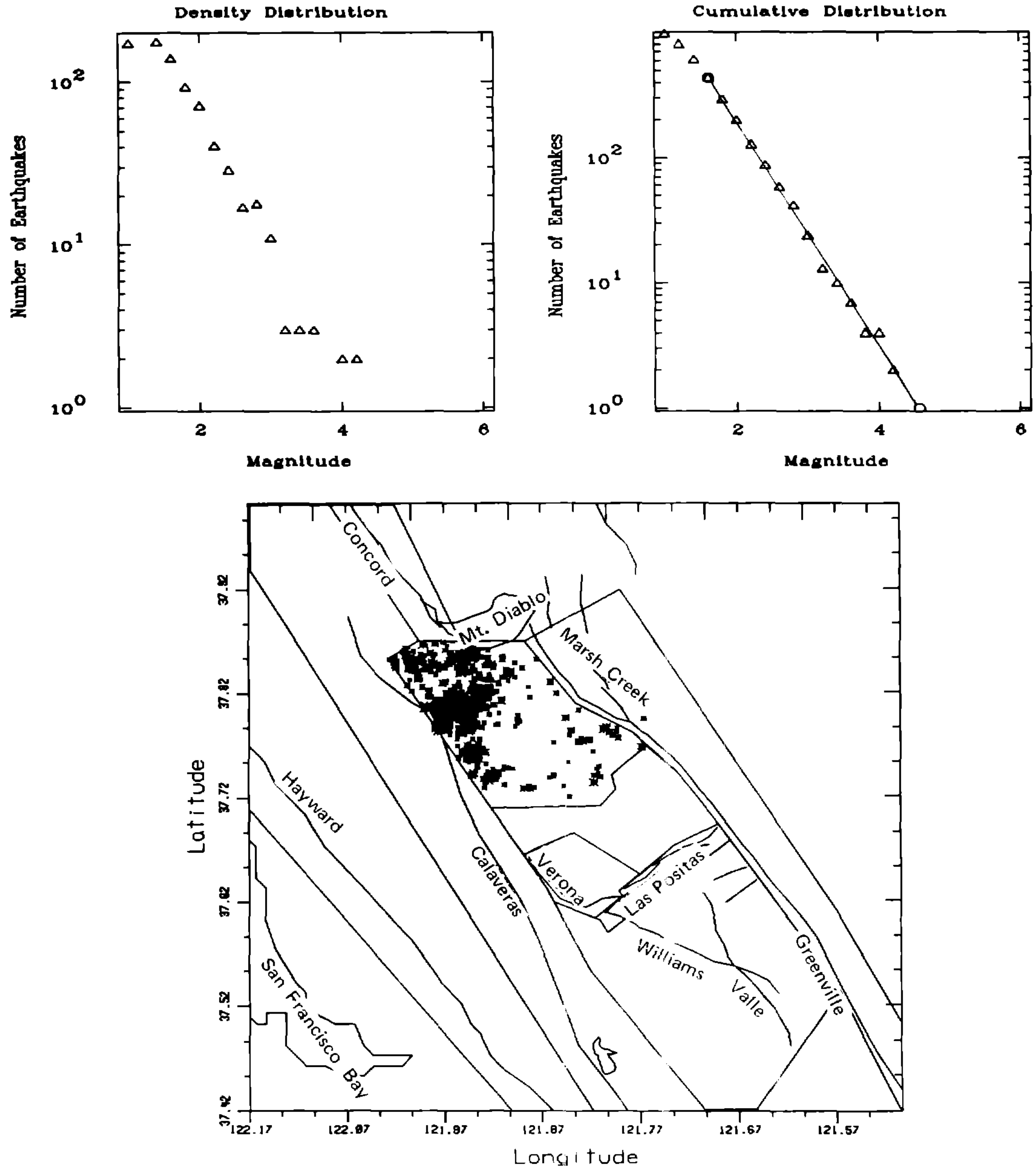


Figure A39. Hazard zone HZ8, Danville Region, using the USGS earthquake catalog. The b-value is 0.888 for $M_L \geq 1.60$

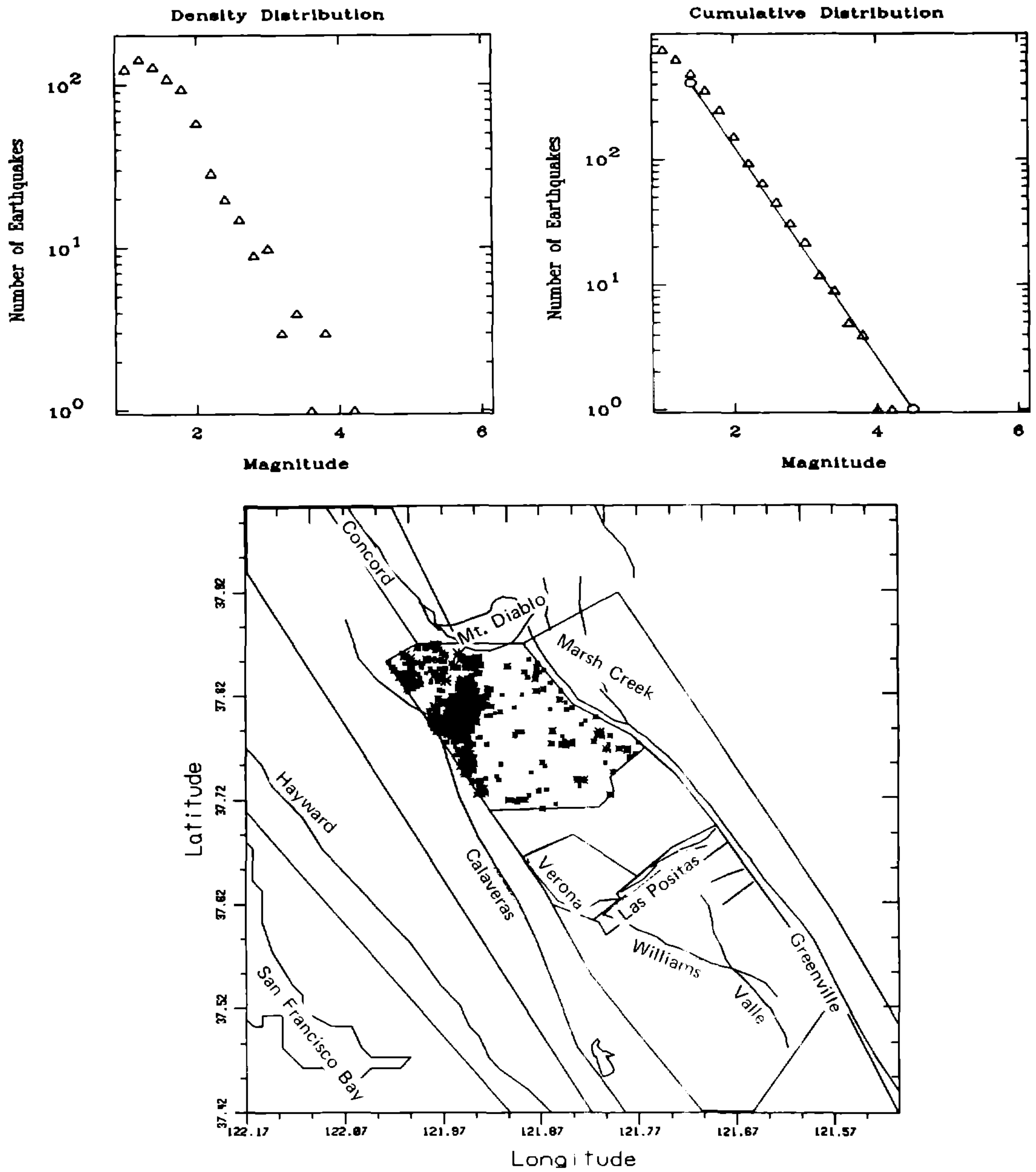


Figure A40. Hazard zone HZ8, Danville Region, using the LLNL earthquake catalog. The b-value is 0.842 for $M_L \geq 1.40$

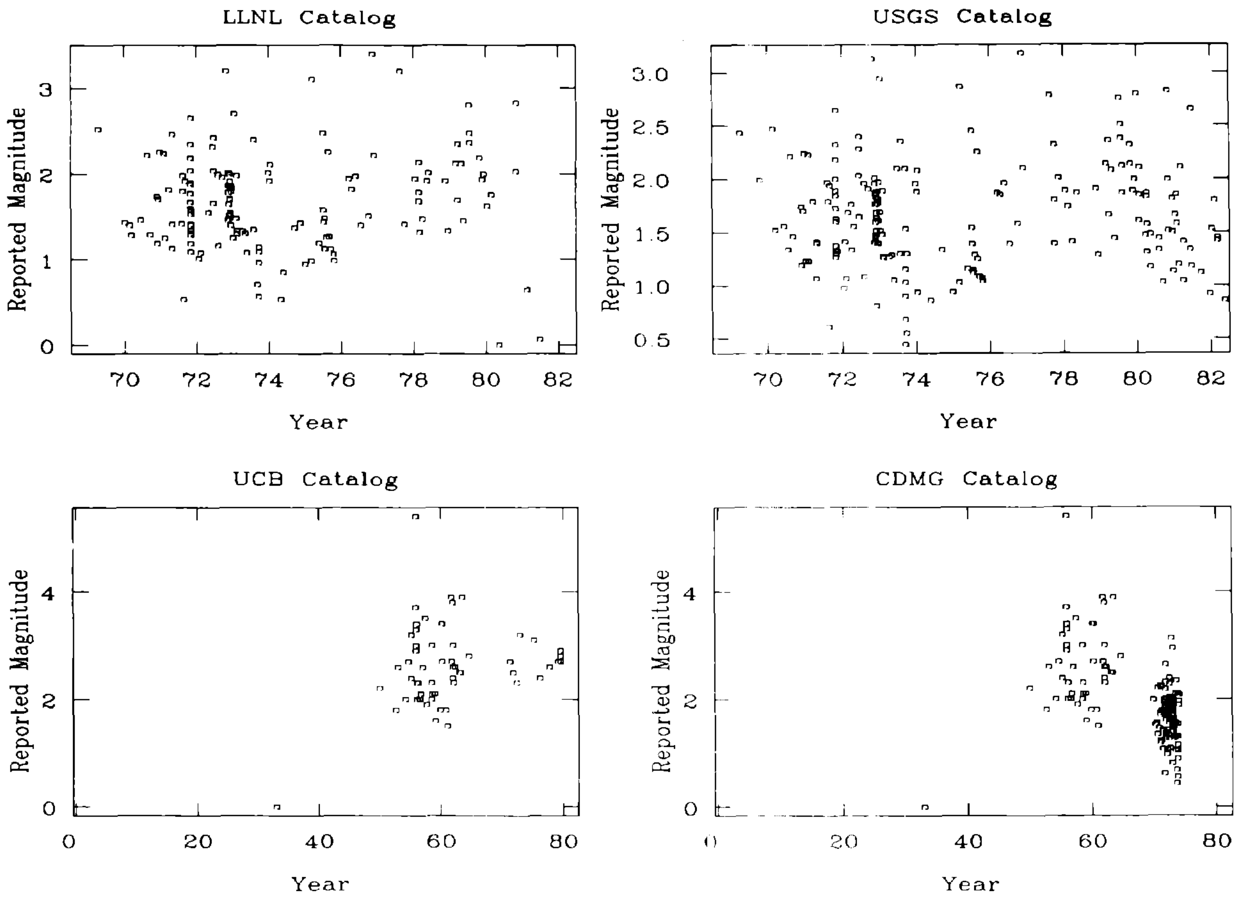


Figure A41. HZ9 - Concord Fault - Plots of reported magnitudes versus time to examine completeness of each of the catalogs.

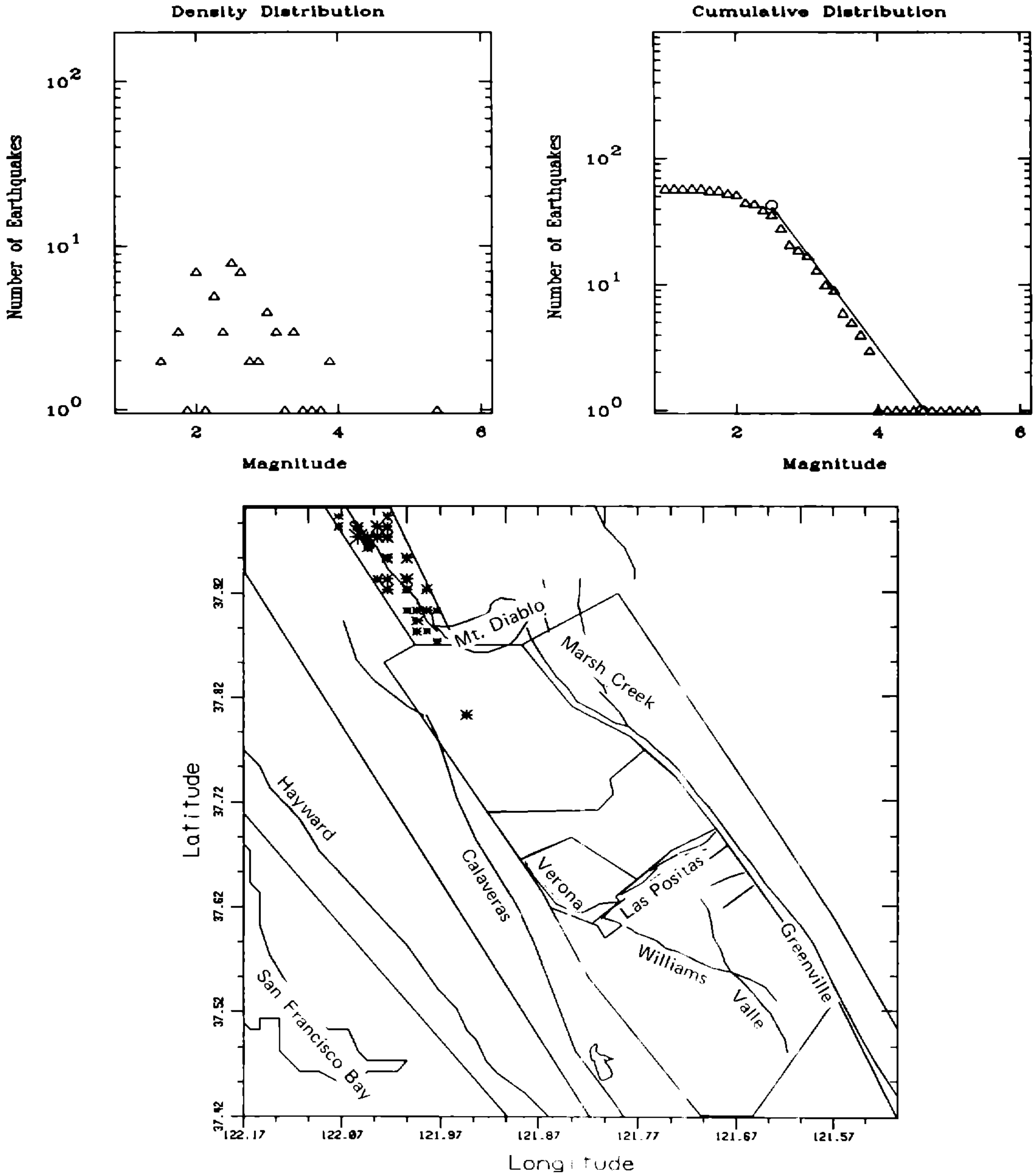


Figure A42. Hazard zone HZ9, Concord Fault, using the UCB earthquake catalog. The b-value is 0.774 for $M_L \geq 2.50$

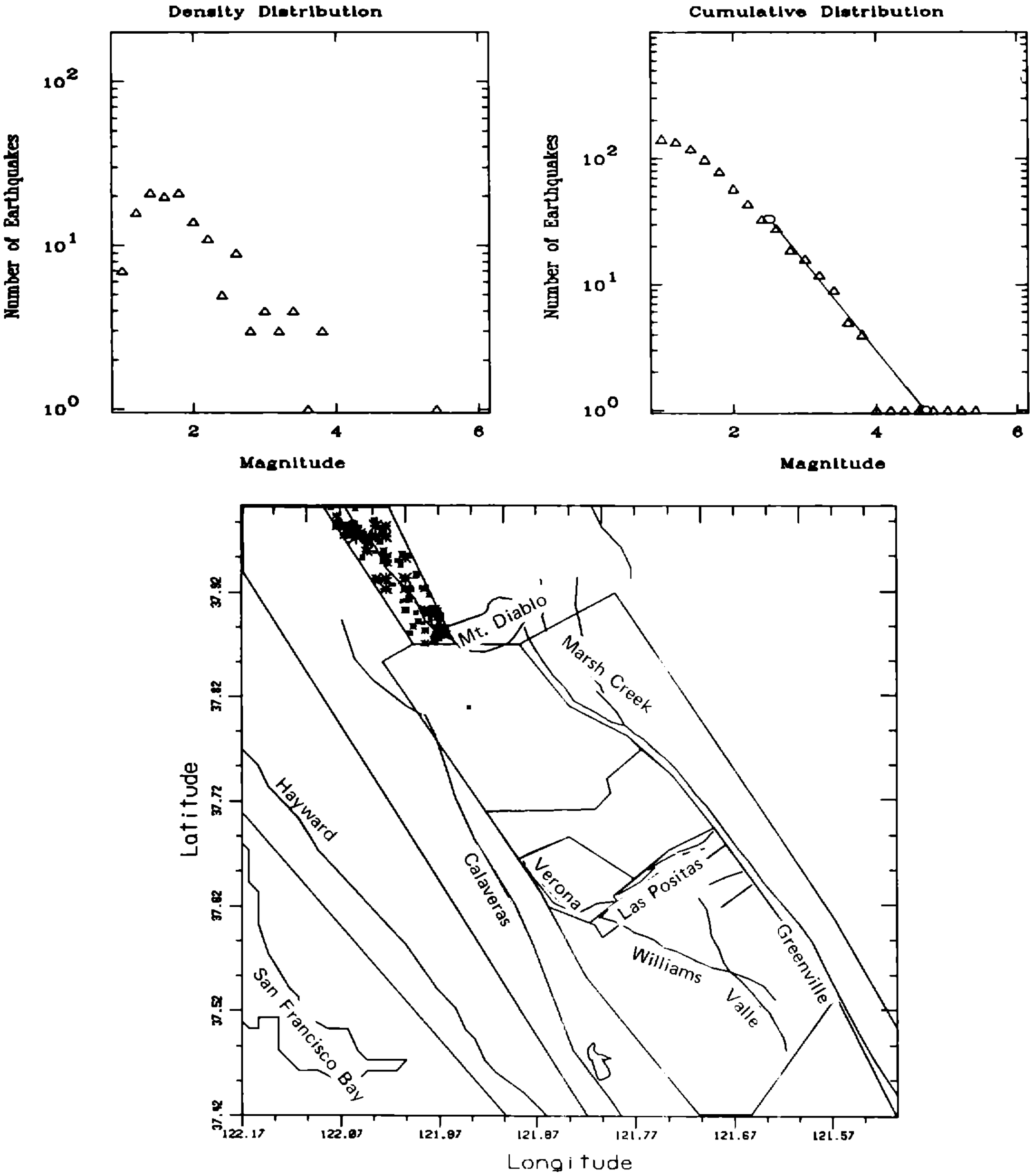


Figure A43. Hazard zone HZ9, Concord Fault, using the CDMG earthquake catalog. The b-value is 0.715 for $M_L \geq 2.50$

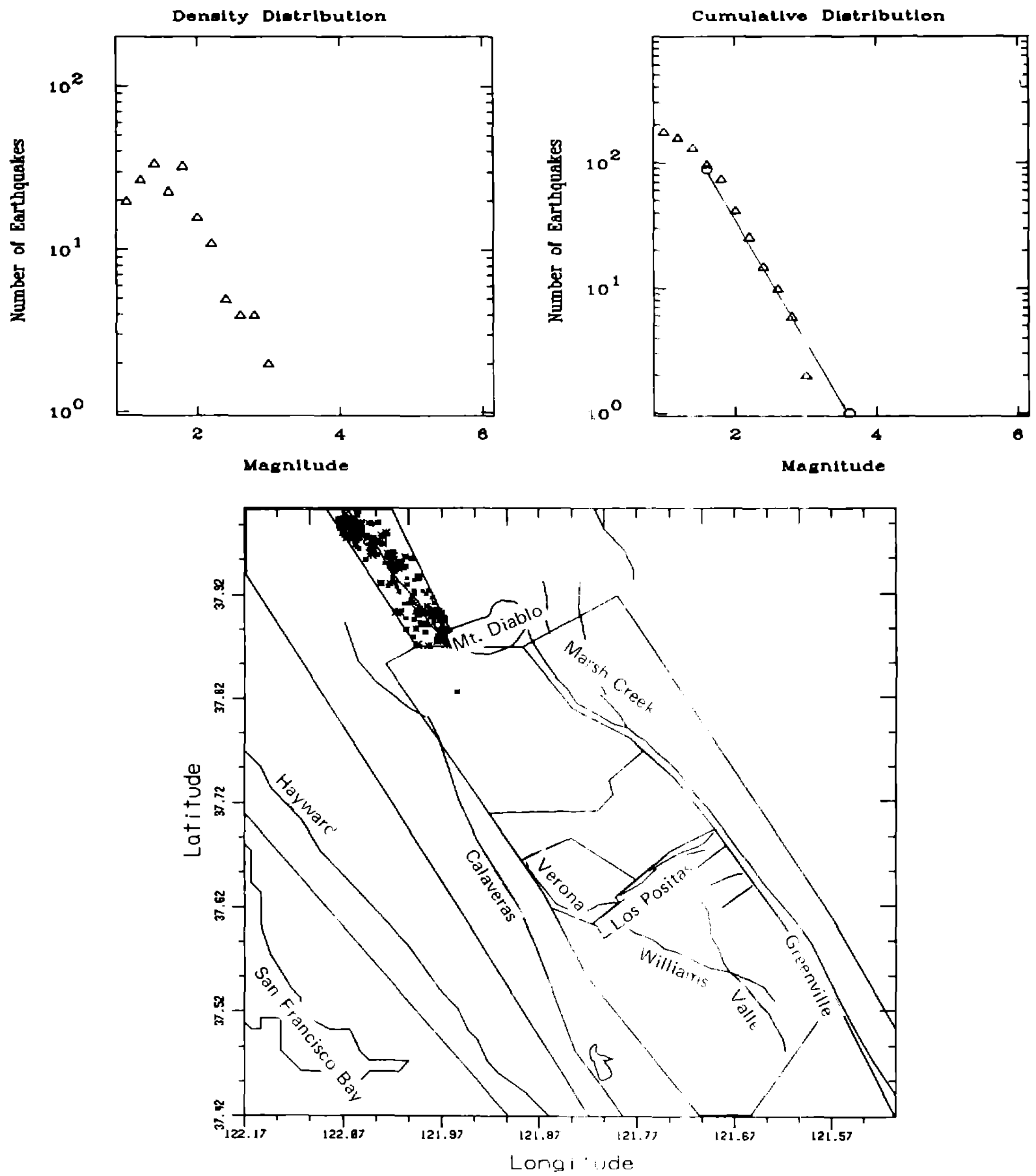


Figure A44. Hazard zone HZ9, Concord Fault, using the USGS earthquake catalog. The b-value is 0.970 for $M_L \geq 1.60$

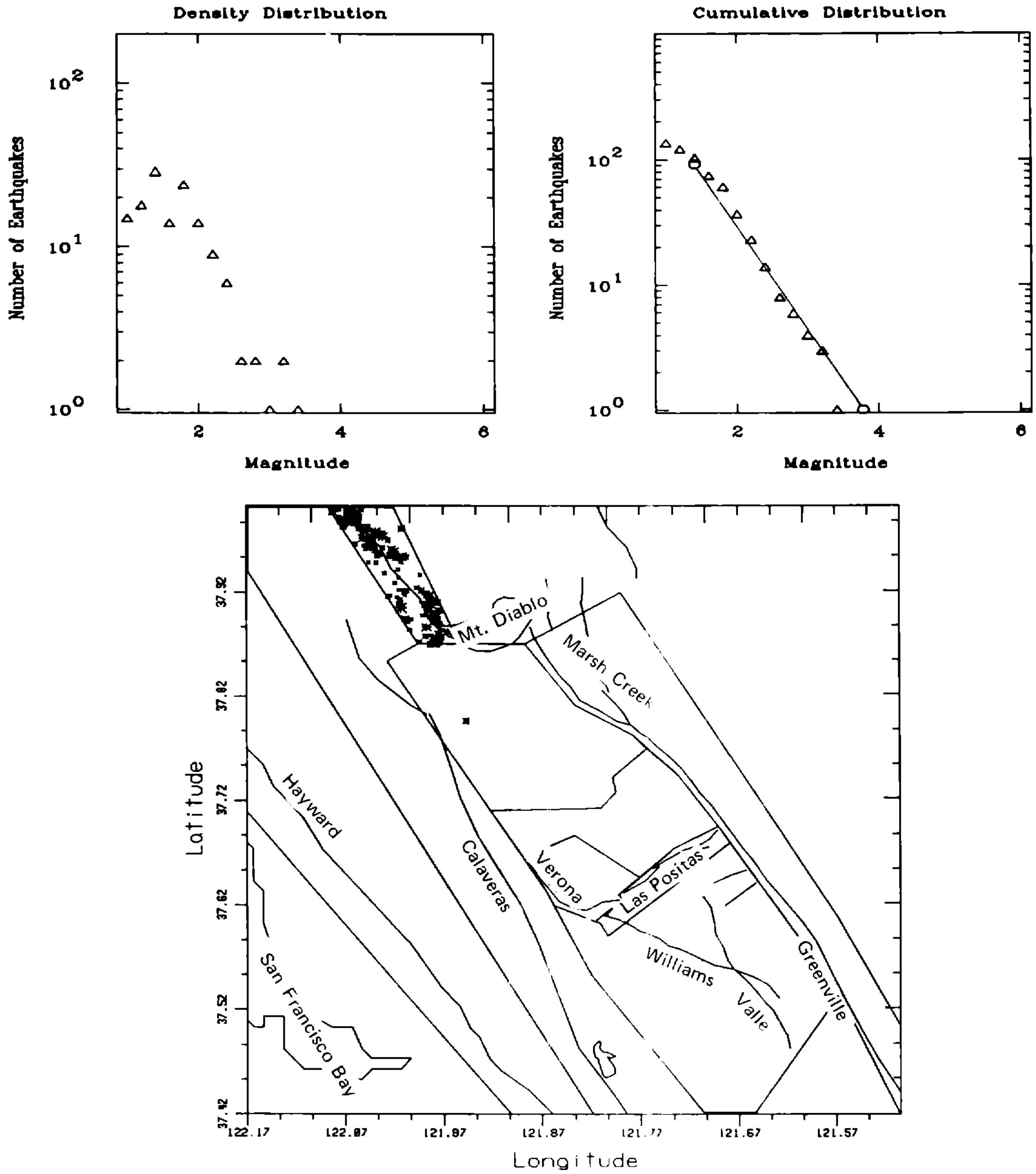


Figure A45. Hazard zone HZ9, Concord Fault, using the LLNL earthquake catalog. The b-value is 0.828 for $M_L \geq 1.40$

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